TECHNICAL MEMORANDUM

NO. 9

AN EVALUATION OF RELATIONSHIPS BETWEEN VEGETATIVE INDICES, SOIL MOISTURE AND WHEAT YIELDS

UNITED STATES DEPARTMENT OF AGRICULTURE
FOREIGN AGRICULTURAL SERVICE

CROP CONDITION ASSESSMENT DIVISION

HOUSTON, TEXAS

NASA-JSC

UNITED STATES DEPARTMENT OF AGRICULTURE
FOREIGN AGRICULTURE SERVICE

AN EVALUATION OF RELATIONSHIPS BETWEEN VEGETATIVE INDICES, SOIL MOISTURE AND WHEAT YIELDS	FIRST ISSUE

Approved By:

Jimmy D. Murphy Jimmy D. Murphy
Director, Crop Condition Assessment Division

1. REASON FOR ISSUANCE

Document the results of this study for use by the Crop Condition Assessment Division (CCAD) of the Foreign Agricultural Service (FAS). The results presented in this document serve as a foundation to future research aimed at identifying predictive relationships between Landsat multispectral scanner data and ground observed measurements such as plant density, plant height, and yield.

2. COVERAGE

The paper presents the relationships among several vegetative indices, relationships between the vegetative indices, soil moisture and a number of ground observed data including plant density, plant height and yield of spring and winter wheat. These relationships were derived with respect to the growth development curve of wheat.

3. PREPARED BY: Andrew C. Aaronson DATE: 17 Sept 79
Andrew C. Aaronson - FAS, CCAD

Larry L. Davis DATE: 17 Sept 79
Larry L. Davis - FAS, CCAD

4. ACKNOWLEDGEMENT

D. McLain for providing the computer software to support this study. E. Bulloch for providing information on soil water holding capacities. Their contributions are gratefully acknowledged.

TABLE OF CONTENTS

Page No.

SEP 18 1979

PART 1.0 INTRODUCTION

1.1 SUMMARY AND CONCLUSIONS

1.1.1 Summary. The mission of the Crop Condition Assessment Division (CCAD) of the Foreign Agricultural Service (FAS) is to verify and assess the impact of adverse conditions on crops in important foreign producing areas and report the results in a timely manner to FAS, Washington, D.C. CCAD crop condition assessment reports are used by FAS commodity analysts, along with other information sources to shape U.S. foreign trade. The timely reporting of crop condition information can be translated into substantial benefits to U.S. foreign trade, the American farmer and consumer.

The CCAD uses many different types of data sources to support its analysis including Landsat, meteorological, soils, and other ancillary data sources.

The CCAD uses Landsat MSS digital data in determining the areal extent of an abnormal event affecting agricultural production and in assessing crop condition. Vegetative Indices (VI's) are computed from the MSS digital data and are used by CCAD analysts to measure the relative "greenness" of agricultural areas. Researchers have developed a number of VI's, all of which are sensitive to the density of the vegetative ground cover. The basis for development of these indices was to reduce the four Landsat spectral bands to their greenness component. The greater the density, or canopy of vegetative areas, the greater the VI. CCAD analysts make qualitative measurements of crop condition by comparing the VI's computed from different areas of a region or country or from the same area for different years. The purpose of this study is to provide the CCAD a basis for developing a capability of using the VI's along with other supportive data sources including soil moisture and crop calendar to accurately measure the condition or yield of a crop.

The objectives of this study were:

1. To identify the VI(s) which provide(s) the most significant relationship to plant height, plant density and yield.

2. To identify the time(s) in the growing season during which the relationship between the VI(s) and plant height, plant density, soil moisture and yield is (are) the strongest.

3. To identify the functional relationship of the VI's, soil moisture, and crop calendar to plant height, plant density and yield.

The VI's* evaluated in the study included the:

1)	Ashburn Vegetative Index	(AVI)
2)	Difference Vegetative Index	(DVI)
3)	Green Vegetative Index**	(GVI)
4)	Kauth Vegetative Index**	(KVI)
5)	Leaf Area Index	(LAI)
6)	Perpendicular Vegetative Index (Band 6)	(PVI6)
7)	Perpendicular Vegetative Index (Band 7)	(PVI7)
8)	Transformed Vegetative Index (Band 6)	(TVI6)
9)	Transformed Vegetative Index (Band 7)	(TVI7)

The data set included ground observed and Landsat digital data collected over 22 blind sites located in North Dakota and Montana during the 1978 spring and winter wheat crop seasons. Ground observed data were collected for 10-15 wheat fields per segment including wheat type, plant height, growth stage, yield and field comments. Landsat data acquired between April and September of 1978 yielded 103 useable acquisitions. Image corrections were exercised on the Landsat data prior to computing the VI's. These corrections included: Landsats 2 and 3 calibration, sun angle correction to a 39° solar zenith angle, and haze correction using the XSTAR algorithm developed by the Environmental Research Institute of Michigan (ERIM).

Soil moisture estimates were added to the data set to determine its relationship to the ground observed data and the VI's. It was hypothesized that the soil moisture estimates would also serve to strengthen the relationship between the ground observed data and the VI's. Meteorological data collected at several weather stations identified near each of the 22 blind sites were used to estimate soil moisture. The Two Layer Soil Moisture Model, used by the National Oceanographic and Atmospheric Administration (NOAA), was used to compute estimates of surface and subsurface soil moisture. The model uses long-term temperatures, current temperatures and precipitation and potential water-holding capacity of the local soils to estimate soil moisture levels.

Correlation and regression analyses were performed on the data set to determine the relationships among the ground observed and soil moisture variables and the VI's. The data set was subdivided into seven growth stage intervals based on the growth stage information obtained for each field within each acquisition.

---

* The VI transformations are shown in Appendix A.

** The GVI is equivalent to the greenness component of the Kauth transform, and the KVI is equivalent to the Green Number used during the Large Area Crop Inventory Experiment.

SEP 18 1979

The growth stage intervals are shown below.

INTERVAL	GROWTH STAGES	LABEL
1	0.0	Planting
2	1.0 - 5.0	Tillering
3	6.0 - 10.0	Stem Extension
4	10.1 - 10.5	Heading
5	10.51 - 10.54	Flowering
6	11.1 - 11.4	Ripening
7	12.0	Harvest

The tillering through ripening growth stage intervals are based on the Feekes scale; while the planting and harvest intervals were added for the purposes of this analysis and were given the 0.0 and 12.0 growth scale definitions, respectively.

The analysis evaluated the relationships among the ground observed and soil moisture variables and the VI's at each of the seven growth stage intervals. It was hypothesized the relationship between a VI and crop condition parameters (such as yield) within a growth interval would more closely approximate a linear relationship.

The correlation results showed that the strength of the relationship between yield and each of the indices at each of the growth stage intervals was approximately the same. The correlations were highest and less variable during the tillering, stem extension and heading growth stage intervals. The average correlation coefficients between the VI's and yield were -.31 at planting, -.26 at tillering, .36 at stem extension, .58 at heading, .17 at flowering, .01 at ripening, and -.42 at harvest. The strongest relationships between final wheat yields and the indices occurred at heading.

Stratification of the data by wheat type (winter or spring wheat) or agrophysical unit (APU) did not significantly affect the relationships between yield and the VI's. Some improvements on the relationship occurred at stem extension, but the relationship remained relatively weak. Stratification of the data by field size did significantly improve the relationship between the indices and yield. The greatest improvements were realized at heading.

Correlation analysis found a strong relationship between plant density, plant height and the indices at tillering and stem extension. Problems with the ground observed data prevented analysis at the later growth stage intervals.

Subsurface soil moisture showed a stronger relationship to yield than was found with surface soil moisture. The relationship peaked at heading producing a correlation coefficient of .59. The relationship remained strong averaging above .45 at the other growth stage intervals, except at stem extension when it dropped to .15.

The strongest relationships determined by the regression analysis occurred at heading and flowering. The coefficient of determination (R^2) and standard deviation between the observed and estimated yields averaged .57 and 5.75, respectively, at heading and .62 and 6.00, respectively, at flowering. The relationships at heading improved significantly by imposing a constraint on minimum field size. At heading the coefficient of determination and standard deviation improved to .81 and 4.08, respectively, after imposing a 30 acre field size constraint. The relationship remained stable after imposing higher minimum acreage limits of 35, 40 and 45 acres.

1.1.2 Conclusions.

- The vegetative indices are highly correlated to each other at each of the seven growth stage intervals.
- The vegetative indices are correlated to wheat yield similarly at each of the seven growth stage intervals. The degree of correlation varies by growth stage interval.
- Each vegetative index is correlated to plant height and density similarly.
- The relationship between wheat yield and the vegetative indices, soil moisture and crop calendar was strongest at heading and flowering.
- There are strong relationships between plant height and density and the vegetative indices, soil moisture and crop calendar at the tillering and stem extension growth stage intervals. The strongest relationships were found at the stem extension growth stage interval.
- An accurate crop calendar for wheat is necessary before attempting to estimate plant density, plant height or wheat yield using vegetative indices and/or soil moisture.

1.2 BACKGROUND

The Crop Condition Assessment Division (CCAD) of the Foreign Agricultural Service (FAS) is responsible for verifying and assessing the impact of adverse conditions on crops in important foreign producing areas and reporting the results to FAS commodity analysts in Wadshington D.C. Foreign crop areas have been identified by FAS that have a significant effect on U.S. foreign trade and are therefore candidate areas for timely analysis by the CCAD. CCAD attention may be drawn to areas undergoing abnormal conditions by its continual screening of Landsat and/or meteorological data. Additionally, the CCAD may be alarmed of events by information sources external to the CCAD, such as by foreign agricultural attaches assigned to these areas. For example, the CCAD may be alerted to a potential drought in the U.S.S.R. which could have a substantial impact on the Soviet wheat crop and its future production. The CCAD will provide timely reports to FAS in Washington on the

condition of the wheat crop, indicating the drought severity and areal extent. FAS commodity analysts will use this information along with other information sources to assess the probable economic impact on the world wheat market relative to U.S. interests.

Methods used by the CCAD for assessing crop conditions using Landsat multispectral scanner (MSS) data include visual screening of the imagery and computer analysis of the digital data. Visual assessments may be qualitative statements describing the condition of the crop, such as the crop looks better or worse than a nominal or reference year. The CCAD currently uses MSS digital data in determining the areal extent of an abnormal event affecting agricultural production and in assessing crop condition. Vegetative indices (VI's) are computed from the MSS digital data and are used by CCAD analysts to measure the relative "greenness" of agricultural areas. Researchers have developed a number of VI's all of which are senstitive to the density of the vegetative ground cover. The basis for development of the VI's was to reduce the four Landsat spectral bands to their greenness component. The greater the density or canopy of vegetative areas the greater the VI. CCAD analysts make qualitative measurements of crop condition by comparing VI's computed from different areas of a region or country or from the same area for different years. The purpose of this study is to provide the CCAD a basis for developing a capability of using the VI's along with other supportive data sources such as soil moisture and crop calendar data to accurately measure the condition or yield of a crop.

For many years, remote sensing and agricultural specialists have believed that predictable relationships exist between crop vegetation and the spectral data. Hass et al (Exhibit 1,A) used Landsat data to qualitatively and quantitatively analyze the amount and seasonal conditions of rangeland vegetation. Quantitative measurements of rangeland condition were made by normalizing the difference between the visible red and infrared channels of Landsat. In essence, Landsat was measuring the amount of green biomass of the rangeland.

Colwell (Exhibit 1,B) used Landsat data to identify annual grasses experiencing moisture stress that could lead to potential fire hazards. In addition, Landsat data were used to identify vegetation affected by frost damage. The study objective was to give early warning of conditions and areas that would require remedial measures to prevent range and forest fires.

The General Electric Company used Landsat data to identify the temporal spectral profile of corn and soybeans in Iowa for the purpose of investigating crop development, condition and yield (Exhibit 1,C). Promising results were obtained in correlating Landsat data to corn yield. Kansas State University used Landsat data to estimate the leaf area index of wheat which is used in an evapotranspiration model. The evapotranspiration estimate is then used in a model to predict the yield of winter wheat (Exhibit 1,D). The results showed that predicted winter wheat yield agreed favorably with the average county yields estimated by the Economics and Statistics Cooperative Service.

Thompson found a high correlation between the Green Number (a vegetative index) and the crop moisture index (CMI) in the U.S. Great Plains (Exhibit 1,E). The Green Number was used successfully in the Large Area Crop Inventory Experiment (LACIE) to monitor and assess drought conditions in the U.S. and foreign areas.

An earlier study by the CCAD found a high correlation between a number of VI's computed over spring wheat fields indicating the VI's measure greenness similarly (Exhibit 1,F).

1.3 PURPOSE

The purpose of this study was to assess the relationship of the Landsat data, in terms of vegetative indices (VI's) to plant parameters, such as plant height, plant density and yield.

The VI's evaluated in this study included the:

1)	Ashburn Vegetative Index	(AVI)
2)	Difference Vegetative Index	(DVI)
3)	Green Vegetative Index 1/	(GVI)
4)	Kauth Vegetative Index 1/	(KVI)
5)	Leaf Area Index	(LAI)
6)	Perpendicular Vegetative Index (Band 6)	(PVI6)
7)	Perpendicular Vegetative Index (Band 7)	(PVI7)
8)	Transformed Vegetative Index (Band 6)	(TVI6)
9)	Transformed Vegetative Index (Band 7)	(TVI7)

The VI transformations are shown in Appendix A.

The objectives of this study were:

1. To identify the VI(s) which provides the most significant relationship to plant height, plant density and yield.

2. To identify the time(s) in the growing season during which the relationship between the VI(s) and plant height, plant density, soil moisture and yield are the strongest.

3. To identify the functional relationship of the VI's, soil moisture, and crop calendar to plant height, plant density, soil moisture and yield.

1.4 DATA SET

1.4.1 Image Data.

1/ The GVI is equivalent to the greenness component of the Kauth transform and the KVI is equivalent to the Green Number used during the LACIE.

1.4.1.1 Segment Location. The image data were extracted from 22 blind sites[2/] identified by the LACIE. Seven of the segments were located in Montana, and the remaining 15 were located in North Dakota (Figure 1-1). The segments were stratified into Agrophysical Units (APU) developed by the LACIE. An APU is a geographic area having similar agricultural and physical characteristics such as similar climate, soils, opography and agricultural density.

1.4.1.2 Observations. Located within each LACIE blind site were 15 spring and/or winter wheat fields for which ground observed information such as plant height, plant density and yield were collected.

The fields in this study varied in size from 9 to 405 acres, averaging 41 acres. Although 15 ground truth fields were available, small fields, clouds, haze and misregistration of the image data limited the number available for analysis to approximately 10 fields per blind site.

Landsat data was acquired between April and September of 1978 and yielded 103 useable acquisitions. Most of the acquisitions were collected during the early and late parts of the growing season as shown below.

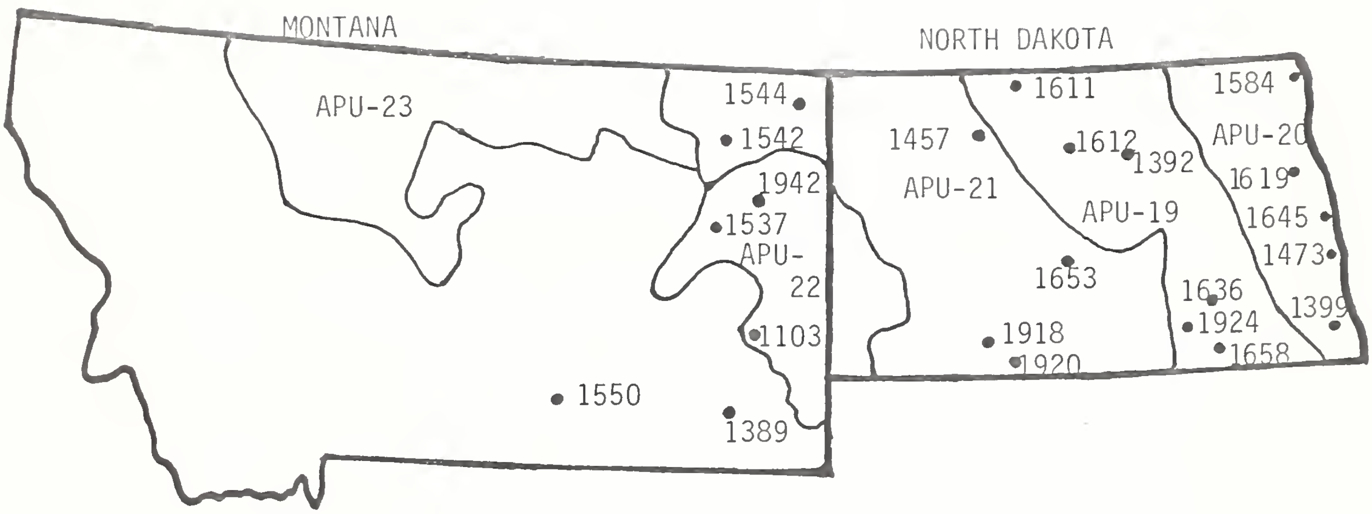
Growth Stage	% of Observations
Planting	9
Tillering	21
Stem Extension	3
Heading	5
Flowering	10
Ripening	30
Harvest	22

The VI statistical mean was computed for each field within each blind site. A total of 980 observations were defined from the 103 useable acquisitions.

1.4.1.3 Image Corrections. Preprocessing of the digital data was exercised prior to the calculation of the VI's. Both Landsat 2 and 3 data were used in the study. Landsat 3 data were calibrated to the Landsat 2 data. Channels 1-4 were multiplied by the calibration values of 1.161, 1.230, 1.246 and 1.062, respectively. These values were developed by the Lockheed Electronics Company and are consistent with those suggested by the Environmental Research Institute of Michican (ERIM) in a recent study "Landsat-3 to Landsat-2 Calibration Transformation", (NASA Contract NAS 9-15476).

2/ A LACIE blind site is a 5x6 nautical mile sample segment for which ground observed data such as field identifications were collected. Blind site information was used by the LACIE to assess the accuracy of crop area classification results achieved by the LACIE analysts.

FIGURE 1-1 AGROPHYSICAL UNIT AND SEGMENT LOCATIONS
IN MONTANA AND NORTH DAKOTA



SEP 18 1979

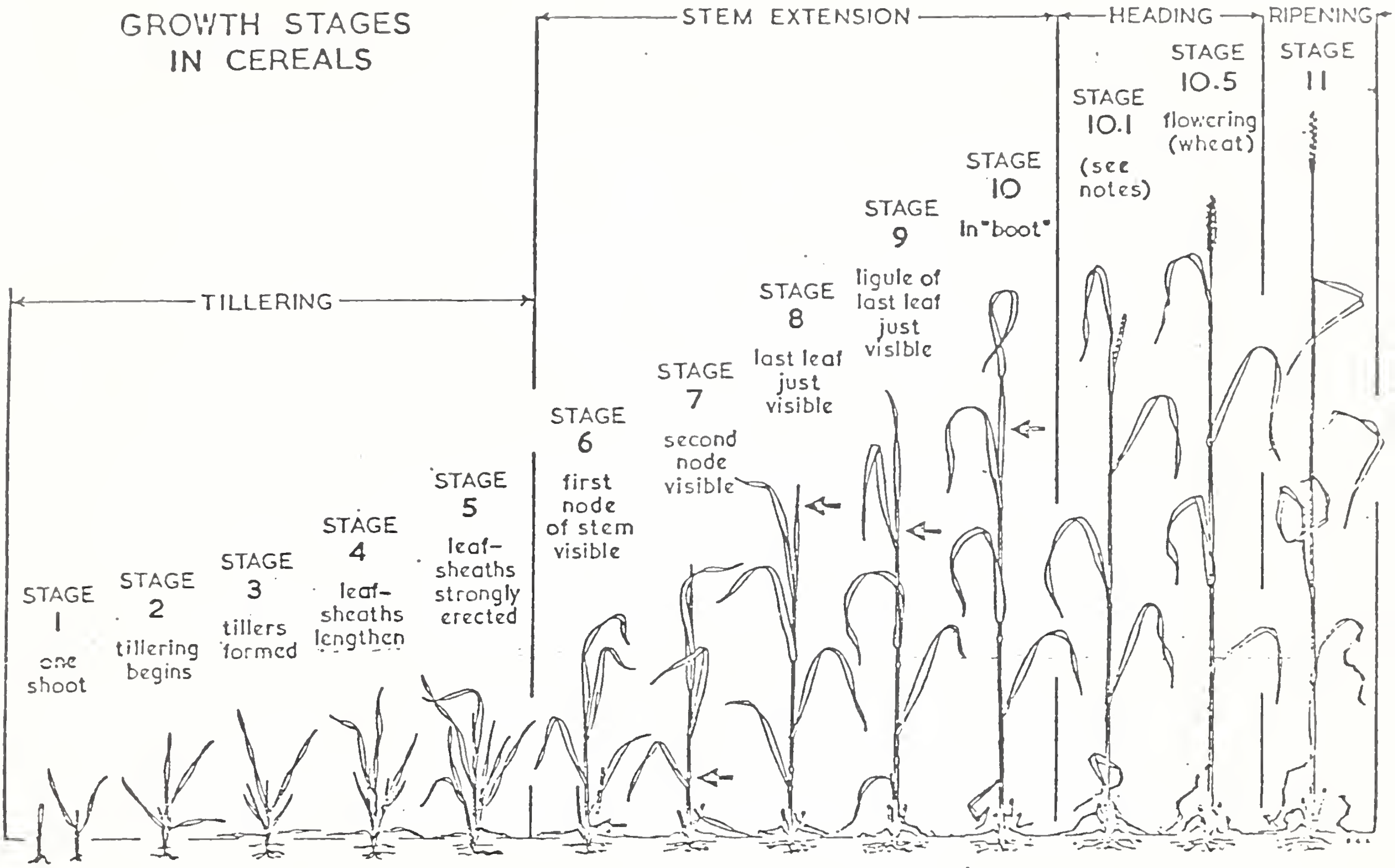
The image data were also sun angle corrected to a 39° solar zenith angle. Sun angle correction compensates for differences in digital radiance due to imagery acquired at different latitudes and at different times during the growing season.

Prior to haze correction, the data were automatically screened for bad data. The screening algorithm flags and removes from the haze correction algorithm those data elements (pixels) that are garbled, clouds, water and cloud shadows. After removing "bad" data, the haze correction algorithm more accurately compensates for the effects of atmospheric attenuation due to haze. The screening and haze algorithms used were the XSTAR developed by ERIM. The XSTAR correction parameters were developed for Landsat 2 data and adjusted to a solar zenith angle of 39°. The ERIM study, previously cited, also indicated that the screening and haze correction functions developed for Landsat 2 data operated reasonably well with calibrated Landsat 3 data.

1.4.2 Ground Observed Data. Ground observed data for the 15 wheat fields consisted of wheat type, plant height (inches), ground cover (percentage), growth stage (Feeke's scale), yield (bushels per acre), and field comments. During the growing season experienced county Agricultural Stabilization and Conservation Service (ASCS) personnel visited the blind sites on satellite overpass days for ground data collection. Ground data information recorded is self-explanatory except for the ground cover and growth stage data. Ground cover, or plant density was recorded as codes 1-5. Each code represented a 20 percent range in ground cover. Growth stage data were recorded according to the stages of wheat development (Figure 1-2) devised by W. Feekes of the Netherlands. The accuracy of the collected ground data can not be ascertained, although highly accurate information would have required a good agronomist. Study of the yield data suggest that it was generally obtained by visual observation, however, farmer estimates were available for some fields.

1.4.3 Soil Moisture Data. Meteorological data collected at weather stations identified near each blind site was used to estimate soil moisture. Temperature and precipitation data were obtained from April through September of 1978 and provided the input to the Two Layer Soil Moisture Model used by the National Oceanographic and Atmospheric Administration (NOAA) to compute their Crop Moisture Index (CMI). The model uses long term temperatures, current temperatures and precipitation, and potential water holding capacity of the soils to estimate soil moisture levels. The surface and subsurface soil moisture estimates obtained from the model are not field specific, but are estimates for the weather stations located in close proximity to the blind sites. Field level soil moisture values would have been preferred for this study since the spectral and ground observed data are both at field level.

FIGURE 1-2 FEEKE'S GROWTH STAGE SCALE FOR WHEAT



Stage		
1	One shoot (number of leaves can be added) = " brairding "	Tillering
2	Beginning of tillering	
3	Tillers formed, leaves often twisted spirally. In some varieties of winter wheats, plants may be " creeping " or prostrate	
4	Beginning of the erection of the pseudo-stem, leaf sheaths beginning to lengthen	
5	Pseudo-stem (formed by sheaths of leaves) strongly erected	
6	First node of stem visible at base of shoot	Stem Extension
7	Second node of stem formed, next-to-last leaf just visible	
8	Last leaf visible, but still rolled up, ear beginning to swell	
9	Ligule of last leaf just visible	
10	Sheath of last leaf completely grown out, ear swollen but not yet visible	
10.1	First ears just visible (awns just showing in barley, ear escaping through split of sheath in wheat or oats)	Heading
10.2	Quarter of heading process completed	
10.3	Half of heading process completed	
10.4	Three-quarters of heading process completed	
10.5	All ears out of sheath	
10.5.1	Beginning of flowering (wheat)	Flowering (Wheat)
10.5.2	Flowering complete to top of ear	
10.5.3	Flowering over at base of ear	
10.5.4	Flowering over, kernel watery ripe	
11.1	Milky ripe	Ripening
11.2	Mealy ripe, contents of kernel soft but dry	
11.3	Kernel hard (difficult to divide by thumb-nail)	
11.4	Ripe for cutting. Straw dead	

1.5 APPROACH

The nominal relationship between a VI and growth stage is shown as Figure 1-3. The temporal profile rises from time of emergence, peaks at or around heading and then drops off sharply to harvest. The shape of the profile for each VI is similar. Those factors affecting the height and/or slope of the temporal profile other than the growth stage factor are variables such as crop condition, varietal differences and cultural practices. Assuming the growth stage information obtained from the ground truth data is fairly accurate, the analysis can then proceed to identify those factors affecting the height and/or slope of the profile.

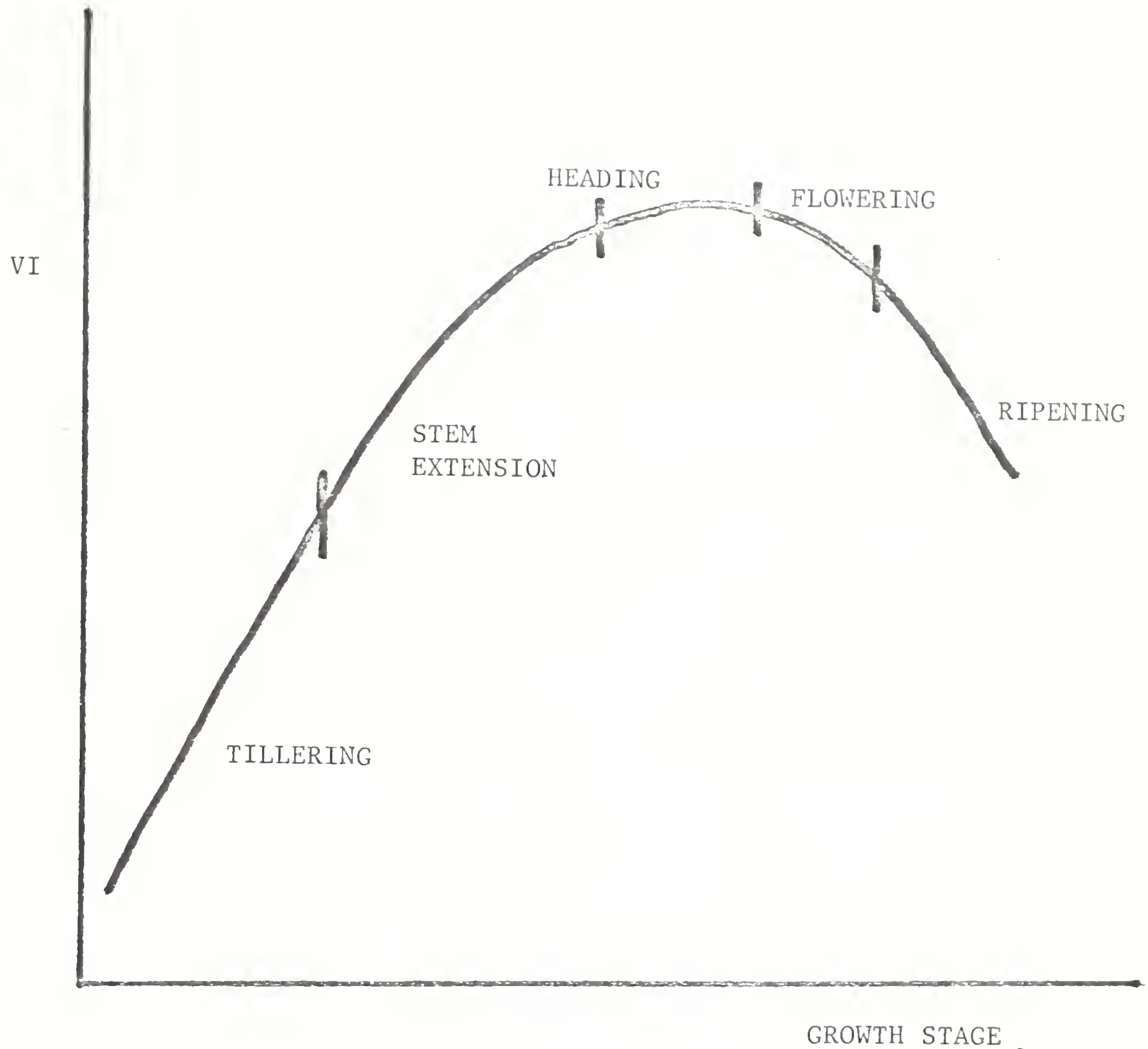
The relationship between a VI and plant density is positive (i.e., as the biomass increases in density, the value of the VI also increases). Nominally, the denser the biomass at a given growth stage, the better the condition of the crop and its yield. There are exceptions to this relationship, but generally the preceding statement is true. One such exception is the case when insects attack the fruit of the crop, but do not affect the vegetative growth. The density of the green biomass remains unaffected and is therefore, undetectable by Landsat.

For purposes of the analysis, the temporal profile was subdivided into seven distinct intervals as shown below. The tillering through ripening growth stage intervals are based on the Feekes scale, while the planting and harvest intervals were added for purposes of this analysis and were given the 0.0 and 12.0 growth scale definitions, respectively.

Interval	Growth Stages	Label
1	0.0	Planting
2	1.0 - 5.0	Tillering
3	6.0 - 10.0	Stem Extension
4	10.1 - 10.5	Heading
5	10.51 - 10.54	Flowering
6	11.1 - 11.4	Ripening
7	12.0	Harvest

Rather than define the profile by a single function, the profile was defined as seven individual ranges or functions. Several transformations were tested to depict the planting through ripening/harvest relationship between a VI and growth stage, but they were not consistent. It was hypothesized the relationship between a VI and crop condition parameters (such as yield) within a growth stage interval would approximate a linear relationship. Changes in the slope of the profile within a given interval are minimal compared to the changes in the slope over the entire probile. The analysis identified the relationships between the VI's and crop condition critireria for each of the seven intervals. A major constraint of the analysis was the uneven distribution of the data within the seven intervals. Those intervals within which the strongest relationships were hypothesized were the stem extension, heading and flowering intervals. Unfortunately, they accounted for only 18 percent of the data. The uneven distribution of the data across the growth stage intervals was a severe limitation in this study.

FIGURE 1-3 RELATIONSHIP BETWEEN GROWTH STAGE AND A VI



Part 2.0 reports the results of the evaluation of general relationships between the VI's and ground observed data at each of the seven intervals. The surface and subsurface soil moisture levels were added to the data set to improve the likelihood of identifying a strong and repeatable relationship between yield and the indices. It was felt the VI's, along with surface and subsurface soil moisture parameters, would account for a larger percentage of the variation in yield, than would be achieved by using the indices alone.

Correlation analysis was used to determine the strength of the relationships between the VI's and crop data at each growth stage interval. Specifically, all the VI's were correlated to each other, plant height, plant density, growth stage, yield, and surface and subsurface soil moisture. A matrix of correlation coefficients and significance levels at each growth stage interval is presented in Part 2.0. It was hypothesized that the relationship between the VI's and plant density, plant height and yield would strengthen as the plant progressed through its growth cycle reaching the strongest relationship at heading and flowering, and weakening at ripening and harvest time.

Additionally, analysis of the coefficient of variation (CV) of a VI at a given growth stage was implemented to determine if the CV of a VI is reduced by stratifying the observations into predefined yield intervals versus the CV of a VI across all yields (unstratified). The observations were stratified into five bushel/acre yield intervals from 10-14 bu/ac to 60-64 bu/ac. Yields ranged from a low of 12 bu/ac to a high of 63 bu/ac and averaged 34.5 bu/ac.

The data were further analyzed to determine the effects of field size, wheat type (winter or spring) and APU location on the relationships between the VI's and the crop data. Correlation coefficients were computed for each of the three field size ranges: greater than 30, 40, and 50 pixels[2/]. It was felt the relationship would strengthen as the minimum field size was increased. Increasing the minimum field size would reduce the effect of edge or border pixels on the VI statistical mean computed for each field. Correlation coefficients were computed separately for those winter wheat and spring wheat observations. This analysis would indicate the effects of wheat type on the relationships of the VI's to plant density, plant height, and yield. Correlation coefficients were also computed for those observations contained in each of four APU's. It was hypothesized that relationships would strengthen as effects due to soils, topography and climate were minimized. An APU is a geographic area having similar physical and agricultural characteristics, such as similar soils, topography, agricultural density and climate.

Part 3.0 presents the results of the regression analysis performed on the data set. A stepwise regression procedure was performed at each of the seven growth stage intervals for each of nine VI's using yield, plant density and plant height as the dependent variables and the VI's, surface and subsurface soil moisture, growth stage and a number

---

2/ A pixel or picture element is the smallest area for which reflectance measurements are collected by Landsat. A Landsat pixel is approximately 1.1 acres in size.

of interactive terms as the independent variables. Relationships were compared for each VI by growth stage interval in an effort to define the time in the growing season when the strongest relationship occurs. Additionally, the regression results for all the VI's were compared to one another by growth stage interval in an effort to identify the VI that provided the strongest relationship to yield. The coefficients of determination (R^2), standard deviations and other associated statistics were computed and are presented in Part 3.0. The standard deviation (i.e., square root of the mean square error ($\sqrt{MSE}$) of the difference between the observed and estimated yield is the principal statistic used in the comparison of the yield relationships. Each regression relationship determined at a given growth stage interval for a VI is based on the identical data set. The only element which varied was the particular VI entered into the analysis. Similar interactive terms were defined for each VI and entered into the stepwise regression procedure. An interactive term is the cross-product between two or more variables, such as the cross-product of a VI and soil moisture or growth stage (e.g., AVI*Soil Moisture).

A 10 percent level of significance was introduced as a constraint for the entry of a variable into the regression relationship.

The Statistical Analysis System (SAS) software routines were used to analyze the data. SAS is an integrated system for data management and statistical analyses.

1.6 RECOMMENDATIONS FOR FUTURE RESEARCH

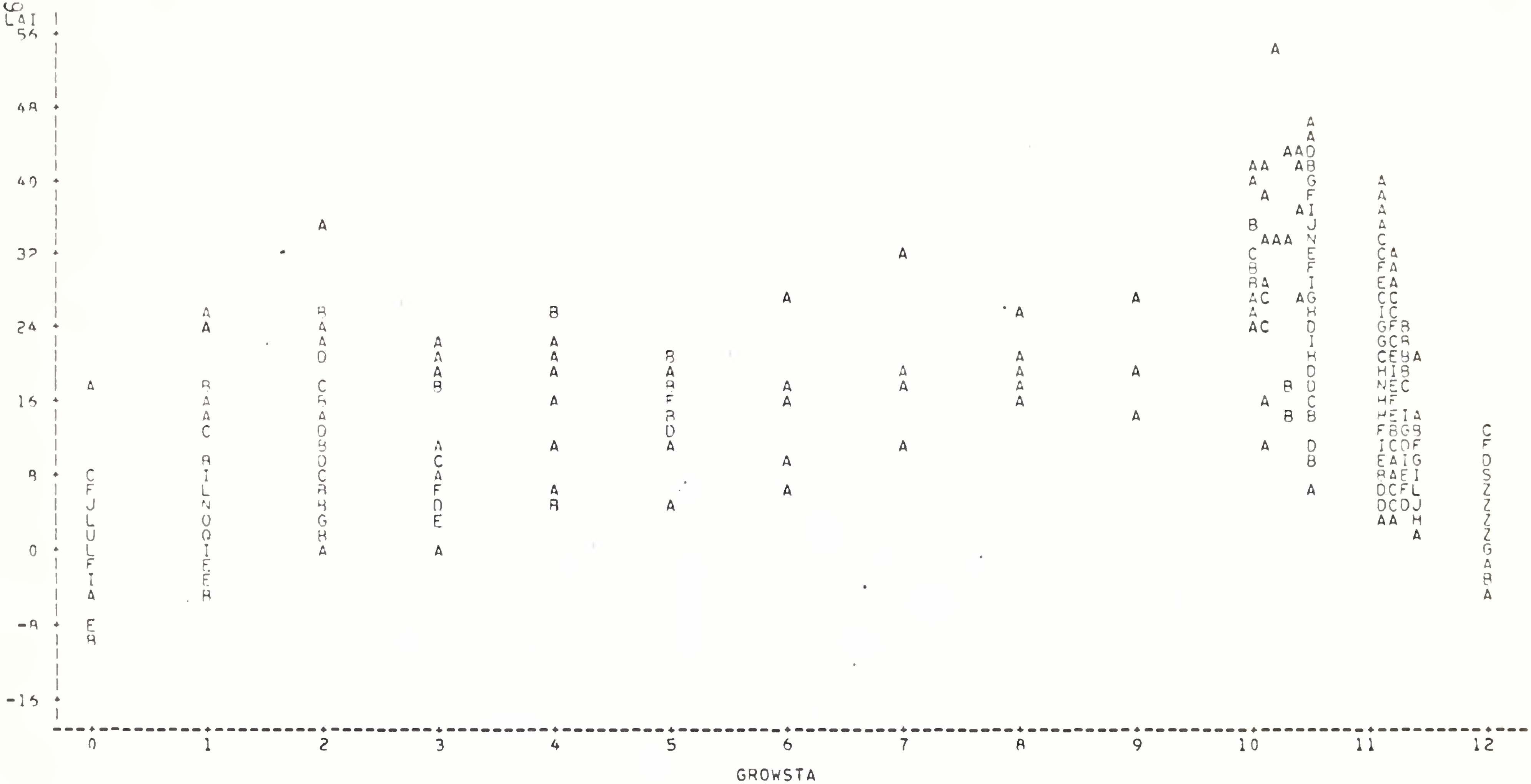
- The acquisition of a complete and accurate set of ground observed and Landsat data to support both static and dynamic analyses of the relationships between crop condition parameters such as biomass and yield, and the Landsat data is recommended.

- An in-depth analysis of what effects soils, geographic location and/or other factors have on these relationships is strongly recommended.

- Actual field level measurements of soil moisture is recommended rather than using estimates obtained from a soil moisture model. There is a strong indication that the vegetative indices, crop calendar and soil moisture can be used effectively to measure crop condition.

FIGURE 2-1 LAI VS. GROWTH STAGE

PLOT OF LAI*GROWSTA   LEGEND: A = 1 OBS, B = 2 OBS, ETC.



intervals ranged from 10-14 bu/ac to 60-64 bu/ac. The average CV for the eleven yield intervals identified ranged from a high of 400 at emergence to a low of 4.44 at heading and averaged 53. Stratification did not result in an appreciable reduction in the average CV for the eleven yield intervals. However, during the stem extension to flowering intervals the CV was reduced from 28 to 22, a decrease of 21 percent. The variation in the LAI after stratification by yield remained high.

Information on other factors contributing to the large variation in the LAI such as cropping practices was not available and prevented any further conclusive analysis.

2.2.2 Yield and VI's.

2.2.2.1 Over Entire Data Set. The approach used in this study was to identify the relationship between yield and a VI(s) at a point in time (static analysis) versus an approach defining the relationship over time (dynamic analysis). The lack of timely data for a number of fields across the crop calendar prevented a more dynamic analysis. A more dynamic approach would have been preferred, because the yield of a plant is not determined at any one time, but is a combination of many physiological and environmental factors that interact during the entire growth cycle. However, the static approach allowed the analysis to identify the times in the crop calendar during which yield and a VI were strongly correlated.

Figures 2-2 to 2-8 show the relationship between yield and the LAI at each of seven growth stage intervals. A single growth stage within an interval was used to generate the plot in an effort to minimize the variation in the LAI wihin a growth stage interval. For example, growth stage 10.0 of the stem extension growth stage interval was used to generate Figure 2.4 (the stem extension interval extends from growth stages 6.0 - 10.0 on the Feeke's scale).

The relationship between yield and the LAI was highly variable during each growth stage interval. The greatest variations occurred during the planting, tillering, ripening and harvest growth stage intervals, while the least variation occurred during the stem extension, heading and flowering growth stage intervals. The LAI alone was not sufficient for explaining a large percentage of the variation in yield.

Correlation tables were generated for each of the seven growth stage intervals in an effort to identify the strength of the interrelationship between the spectral data and the ground observed data. Correlation Tables 2-1 to 2-7 present these interrelationships (correlation coefficients and significance levels) of 15 variables including nine VI's, three ground observed elements including plant height,

FIGURE 2-2 YIELD VS LAI AT PLANTING

PLOT OF YIELD*LAI LEGEND: A = 1 OBS, B = 2 OBS, ETC.

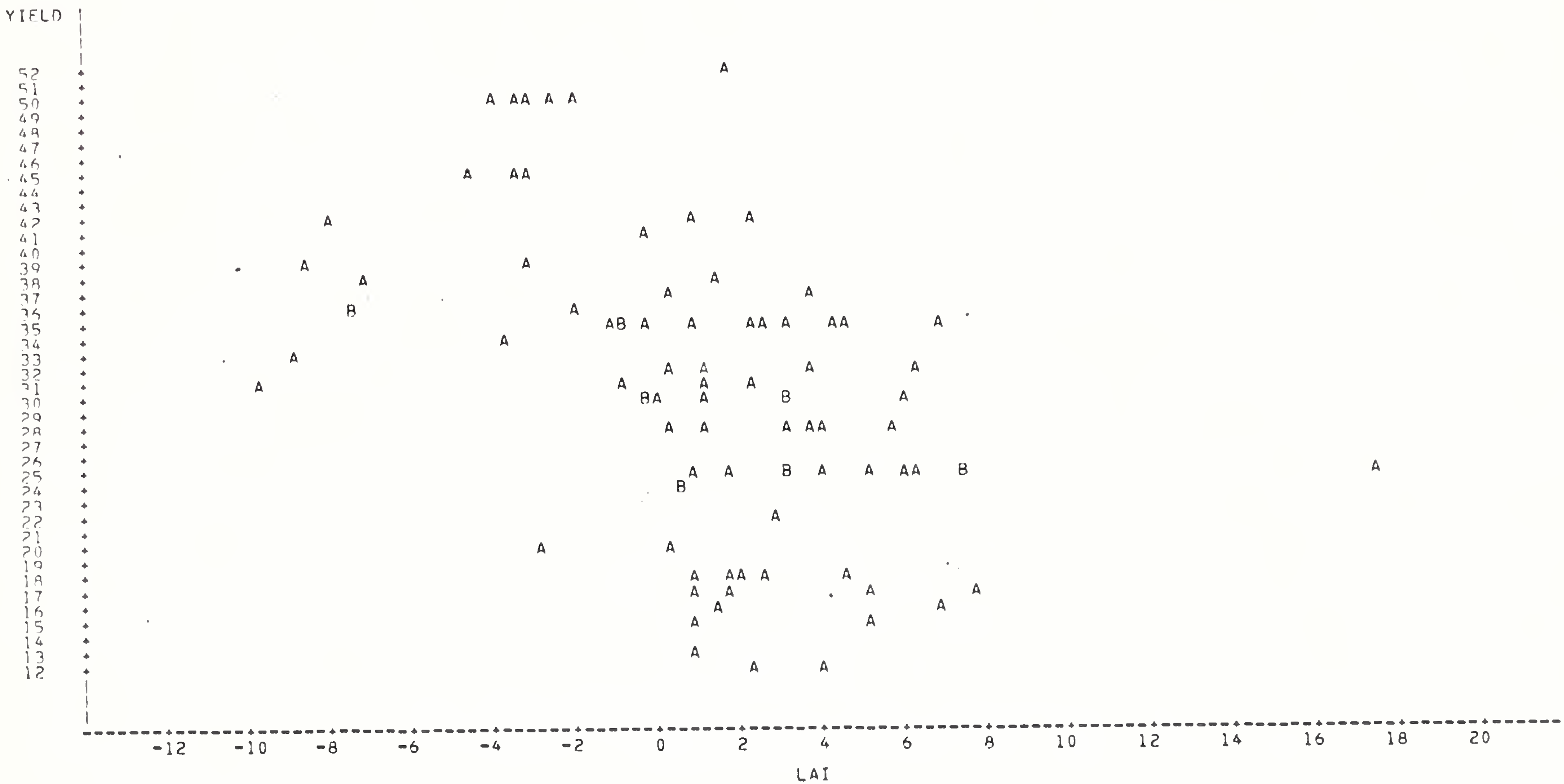
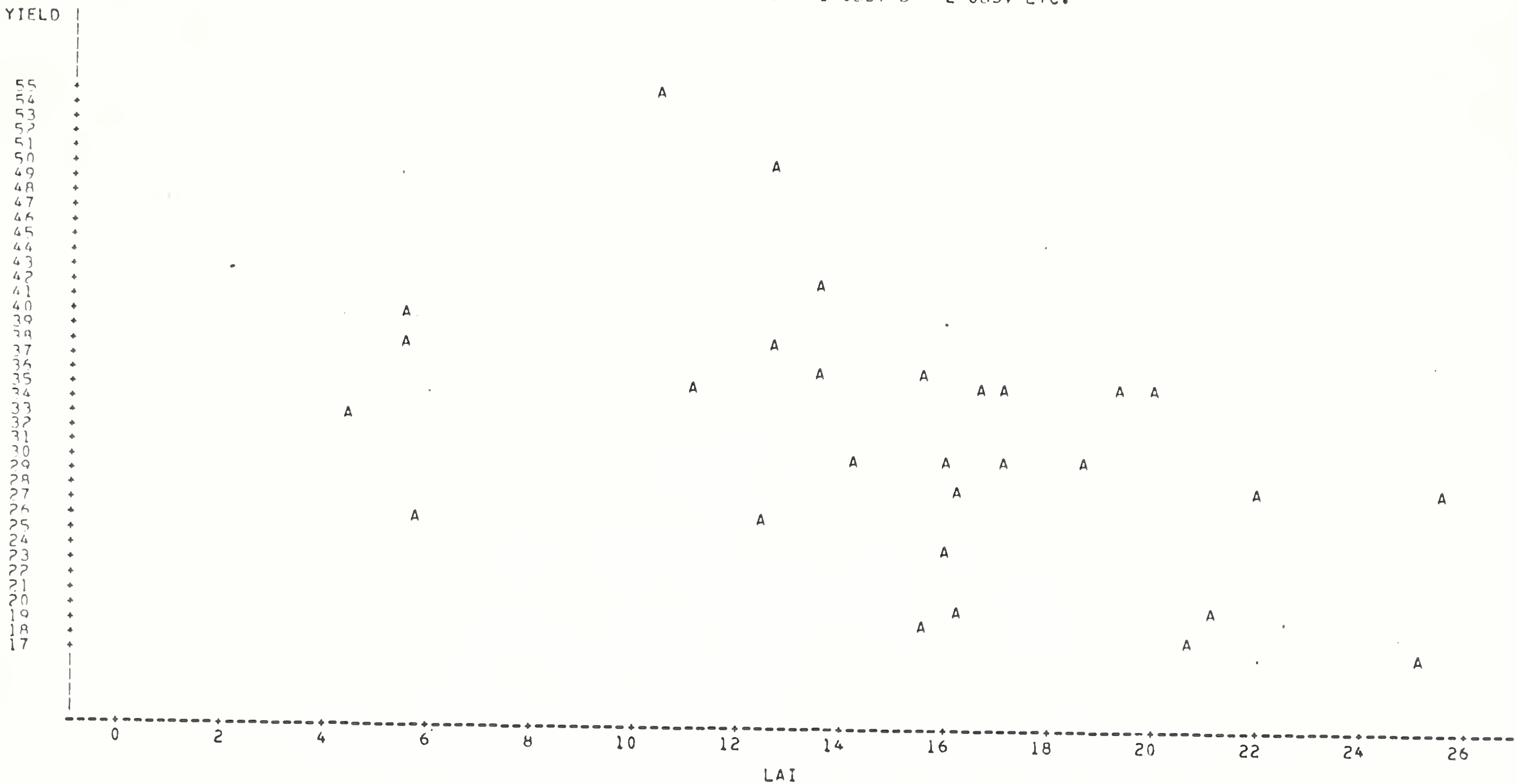


FIGURE 2-3 YIELD VS. LAI AT TILLERING

PLOT OF YIELD*LAI   LEGEND: A = 1 OBS, B = 2 OBS, ETC.



SEP 18 1979

FIGURE 2-4 YIELD VS. LAI AT STEM EXTENSION

PLOT OF YIELD*LAI   LEGEND: A = 1 OBS, B = 2 OBS, ETC.

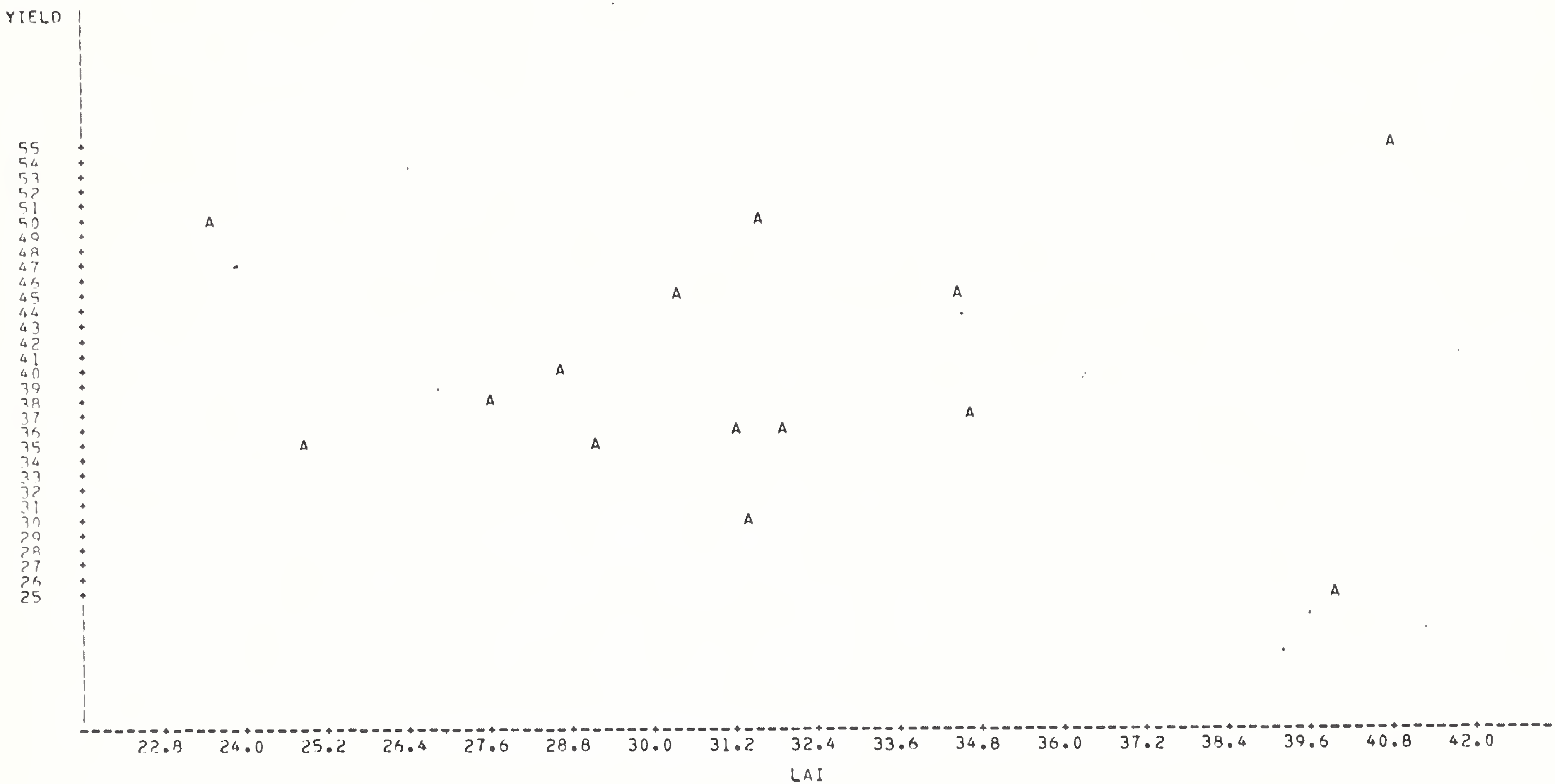


FIGURE 2-5 YIELD VS.LAI AT HEADING

PLOT OF YIELD*LAI   LEGEND: A = 1 OBS, B = 2 OBS, ETC.

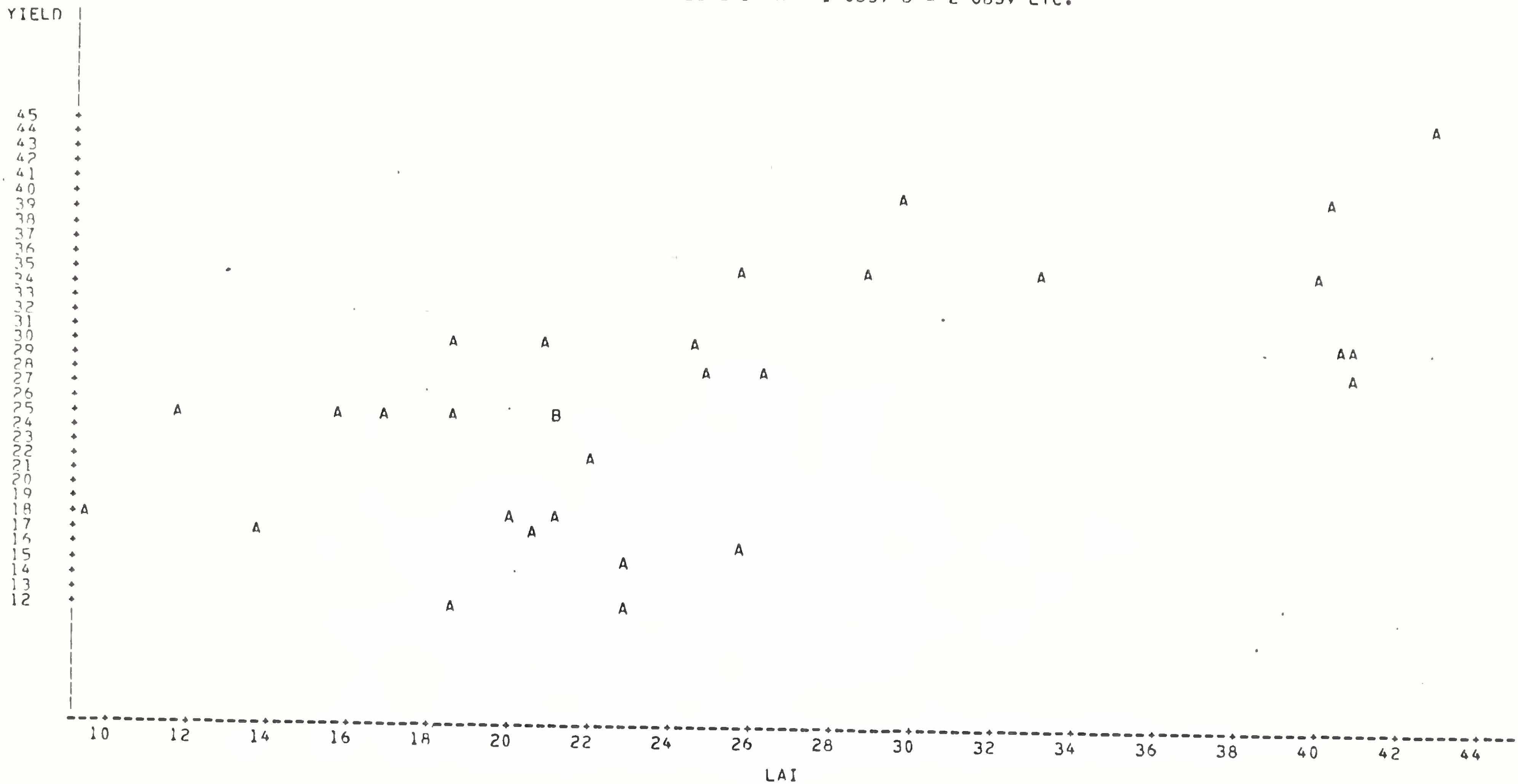


FIGURE 2-6 YIELD VS, LAI AT FLOWERING

PLOT OF YIELD*LAI   LEGEND: A = 1 OBS, B = 2 OBS, ETC.

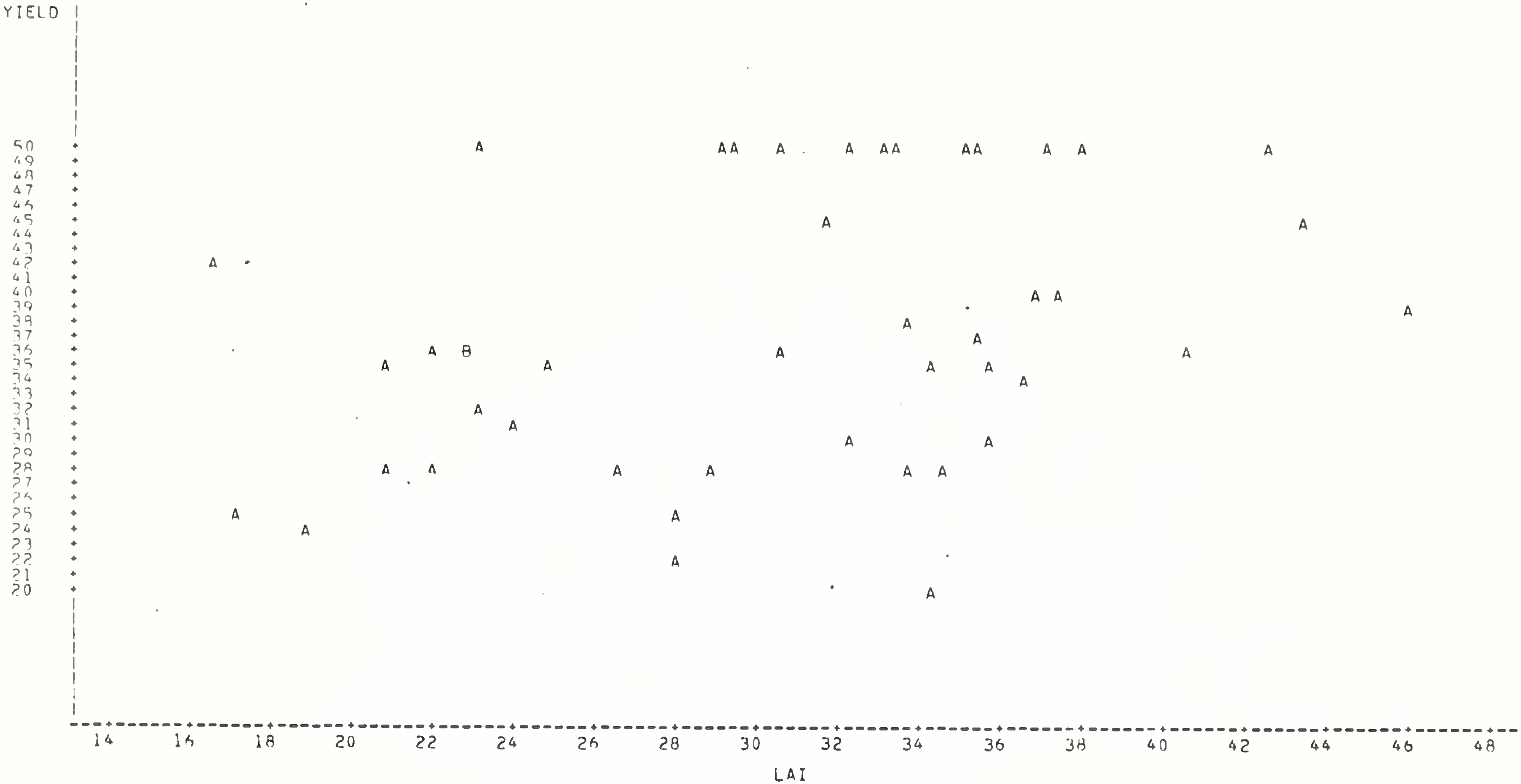


FIGURE 2-7 YIELD VS. LAI AT RIPENING

PLOT OF YIELD*LAI   LEGEND: A = 1 OBS, B = 2 OBS, ETC.

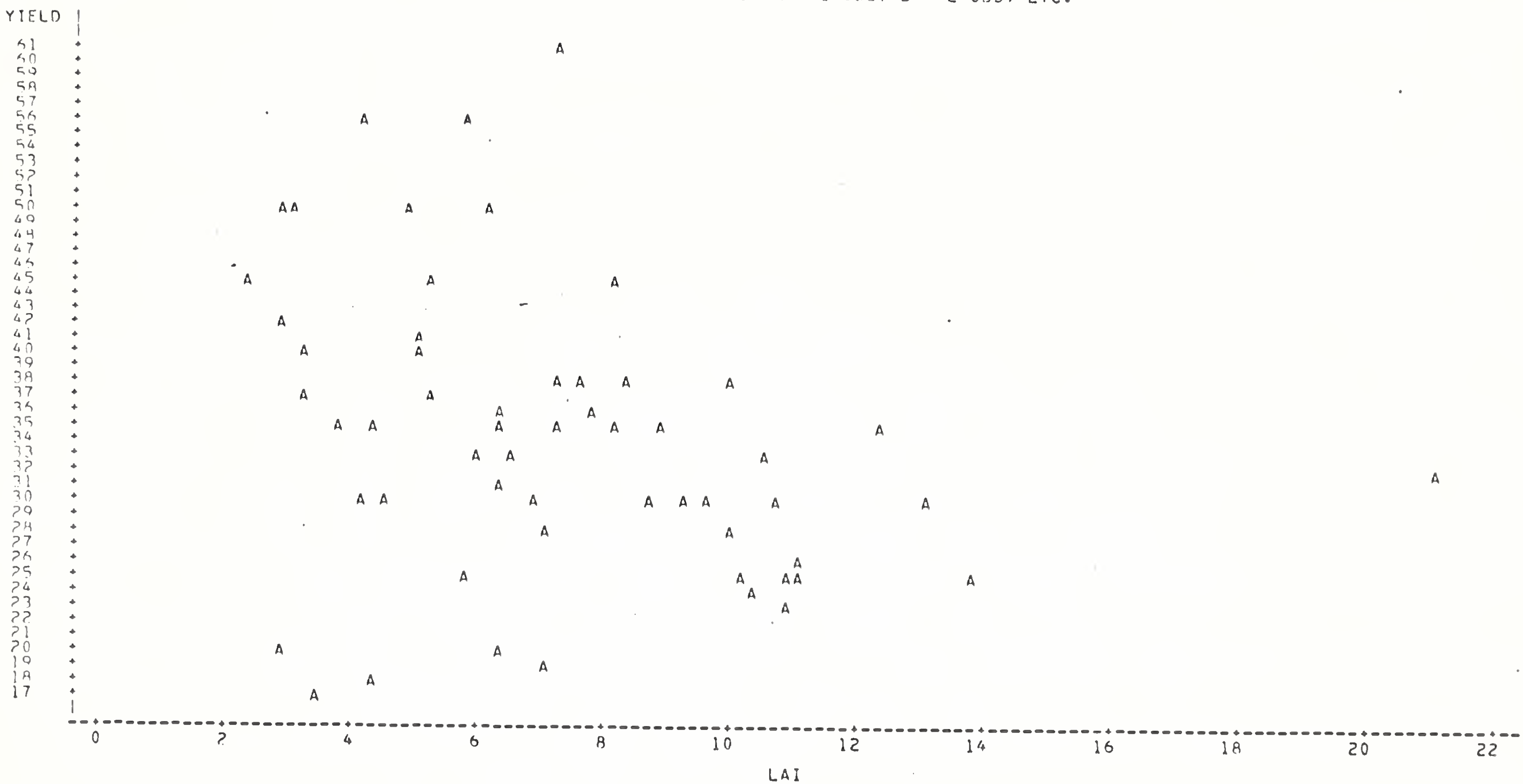


FIGURE 2-8 YIELD VS, LAI AT HARVEST

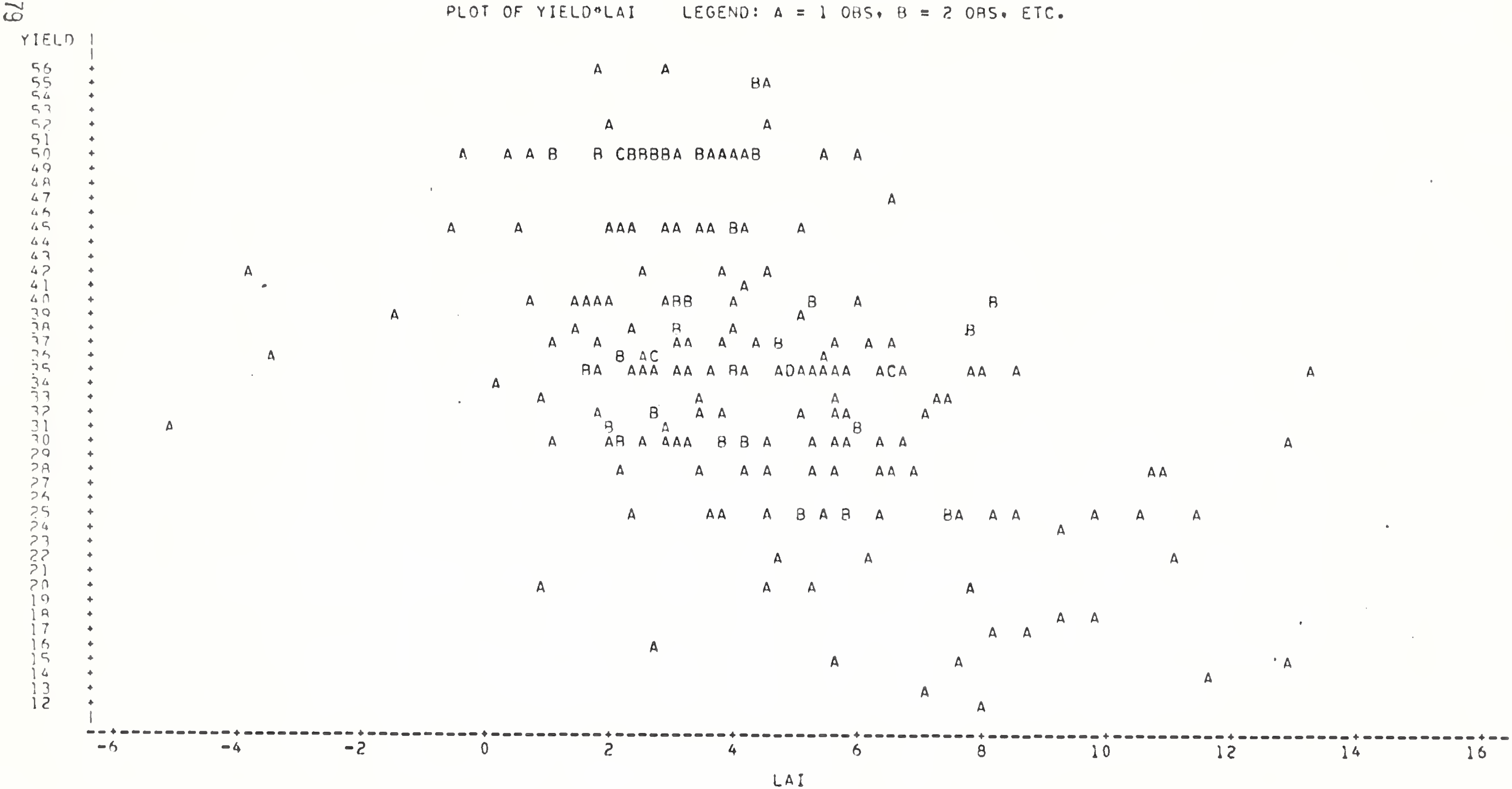


TABLE 2.1 CORRELATIONS AND SIGNIFICANCE LEVELS AT PLANTING

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	YLD[1]	SM1[2]	SM2[3]
AVI	1.00											
DVI	.94 .0001	1.00										
LAI	.66 .0001	.83 .0001	1.00									
GVI	.91 .0001	.97 .0001	.87 .0001	1.00								
KVI	.91 .0001	.97 .0001	.87 .0001	1.00 .0001	1.00							
TVI6	.71 .0001	.87 .0001	.99 .0001	.91 .0001	.91 .0001	1.00						
TVI7	.93 .0001	.98 .0001	.86 .0001	.95 .0001	.95 .0001	.88 .0001	1.00					
PVI6	.75 .0001	.82 .0001	.60 .0001	.84 .0001	.84 .0001	.67 .0001	.73 .0001	1.00				
PVI7	.86 .0001	.94 .0001	.78 .0001	.93 .0001	.93 .0001	.82 .0001	.90 .0001	.91 .0001	1.00			
YIELD	-.12 .2735	-.27 .0115	-.46 .0001	-.35 .0007	-.35 .0007	-.45 .0001	-.24 .0247	-.27 .0108	-.27 .0119	1.00		
SM1	.41 .0001	.49 .0001	.50 .0001	.47 .0001	.47 .0001	.51 .0001	.49 .0001	.32 .0024	.45 .0001	.37 .0005	1.00	
SM2	-.45 .0001	-.56 .0001	-.65 .0001	-.59 .0001	-.59 .0001	-.65 .0001	-.58 .0001	-.34 .0011	-.49 .0001	.55 .0001	-.45 .0001	1.00

[1] YLD = YIELD
[2] SM1 = SURFACE SOIL MOISTURE
[3] SM2 = SUBSURFACE SOIL MOISTURE

SEP 18 1979

TABLE 2.2 CORRELATIONS AND SIGNIFICANCE LEVELS AT TILLERING

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	PLTH[1]	PLTD[2]	GROW[3]	YLD	SM1	SM2
AVI	1.00														
DVI	.98 .0001	1.00													
LAI	.94 .0001	.95 .0001	1.00												
GVI	.98 .0001	.99 .0001	.96 .0001	1.00											
KVI	.98 .0001	.99 .0001	.96 .0001	1.00 .0001	1.00										
TVI6	.94 .0001	.97 .0001	.99 .0001	.97 .0001	.97 .0001	1.00									
TVI7	.98 .0001	.97 .0001	.97 .0001	.97 .0001	.97 .0001	.97 .0001	1.00								
PVI6	.89 .0001	.95 .0001	.91 .0001	.96 .0001	.96 .0001	.93 .0001	.89 .0001	1.00							
PVI7	.96 .0001	.99 .0001	.95 .0001	.98 .0001	.98 .0001	.97 .0001	.97 .0001	.96 .0001	1.00						
PLTH	.63 .0001	.66 .0001	.64 .0001	.69 .0001	.69 .0001	.67 .0001	.63 .0001	.70 .0001	.67 .0001	1.00					
PLTD	.47 .0001	.49 .0001	.45 .0001	.51 .0001	.51 .0001	.48 .0001	.46 .0001	.51 .0001	.50 .0001	.52 .0001	1.00				
GROW	.47 .0001	.55 .0001	.48 .0001	.56 .0001	.56 .0001	.54 .0001	.46 .0001	.65 .0001	.56 .0001	.71 .0001	.72 .0001	1.00			
YIELD	-.22 .0021	-.26 .0002	-.30 .0001	-.26 .0002	-.26 .0002	-.30 .0001	-.25 .0003	-.25 .0003	-.27 .0001	-.10 .1574	-.07 .3305	-.12 .0807	1.00		
SM1	-.07 .2997	-.05 .4959	-.03 .6824	-.07 .3505	-.07 .3505	-.03 .6251	-.04 .5856	-.07 .3301	-.05 .4795	.04 .5603	-.20 .0034	.05 .5056	-.17 .0140	1.00	
SM2	-.23 .0011	-.29 .0001	-.32 .0001	-.27 .0001	-.27 .0001	-.33 .0001	-.27 .0002	-.33 .0001	-.29 .0001	-.09 .1995	-.18 .0089	-.13 .0662	.43 .0001	-.06 .3902	1.00

[1] PLTH = PLANT HEIGHT
[2] PLTD = PLANT DENSITY
[3] GROW = GROWTH STAGE

SEP 18 1979

TABLE 2-3 CORRELATIONS AND SIGNIFICANCE LEVELS AT STEM EXTENSION

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	PLTH	PLTD	GROW	YLD	SM1	SM2
AVI	1.00														
DVI	1.00 .0001	1.00													
LAI	.98 .0001	.93 .0001	1.00												
GVI	.99 .0001	.99 .0001	.98 .0001	1.00											
KVI	.99 .0001	.99 .0001	.98 .0001	1.00 .0001	1.00										
TVI6	.98 .0001	.95 .0001	.99 .0001	.98 .0001	.98 .0001	1.00									
TVI7	.99 .0001	.97 .0001	.99 .0001	.98 .0001	.98 .0001	.99 .0001	1.00								
PVI6	.98 .0001	.98 .0001	.96 .0001	.99 .0001	.99 .0001	.96 .0001	.96 .0001	1.00							
PVI7	1.00 .0001	1.00 .0001	.97 .0001	.99 .0001	.99 .0001	.97 .0001	.98 .0001	.99 .0001	1.00						
PLTH	.83 .0001	.84 .0001	.76 .0001	.82 .0001	.82 .0001	.77 .0001	.79 .0001	.82 .0001	.84 .0001	1.00					
PLTD	.65 .0001	.65 .0001	.68 .0001	.68 .0001	.68 .0001	.71 .0001	.68 .0001	.67 .0001	.65 .0001	.51 .0030	1.00				
GROW	.69 .0001	.68 .0001	.71 .0001	.70 .0001	.70 .0001	.73 .0001	.71 .0001	.69 .0001	.69 .0001	.72 .0001	.75 .0001	1.00			
YIELD	.37 .0385	.36 .0456	.38 .0347	.35 .0514	.35 .0514	.36 .0460	.40 .0248	.30 .0953	.36 .0458	.37 .0379	.40 .0260	.22 .2236	1.00		
SM1	.00 .9776	-.01 .9414	.06 .7658	-.02 .9048	-.02 .9048	.02 .8956	.04 .8359	-.04 .8191	-.01 .9497	-.09 .6276	.15 .4206	.21 .2484	.13 .4953	1.00	
SM2	-.14 .4574	-.13 .4701	-.23 .2209	-.18 .3396	-.18 .3396	-.19 .2982	-.16 .3841	-.20 .2778	-.13 .4620	.09 .6431	-.45 .0097	-.37 .0403	.15 .4178	-.32 .0741	1.00

TABLE 2-4 CORRELATIONS AND SIGNIFICANCE LEVELS AT HEADING

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	GROW	YLD	SM1	SM2
AVI	1.00												
DVI	1.00 .0001	1.00											
LAI	.95 .0001	.93 .0001	1.00										
GVI	.99 .0001	.99 .0001	.95 .0001	1.00									
KVI	.99 .0001	.99 .0001	.95 .0001	1.00 .0001	1.00								
TVI6	.97 .0001	.95 .0001	.99 .0001	.98 .0001	.98 .0001	1.00							
TVI7	.98 .0001	.97 .0001	.98 .0001	.97 .0001	.97 .0001	.99 .0001	1.00						
PVI6	.97 .0001	.98 .0001	.93 .0001	.99 .0001	.99 .0001	.95 .0001	.94 .0001	1.00					
PVI7	1.00 .0001	1.00 .0001	.93 .0001	.99 .0001	.99 .0001	.95 .0001	.97 .0001	.98 .0001	1.00				
GROW	-.09 .5007	-.10 .4640	-.11 .4178	-.15 .2707	-.15 .2707	-.13 .3243	-.09 .5055	-.19 .1604	-.10 .4639	1.00			
YIELD	.54 .0001	.53 .0001	.64 .0001	.59 .0001	.59 .0001	.63 .0001	.60 .0001	.59 .0001	.53 .0001	-.27 .0392	1.00		
SM1	.25 .0658	.25 .0599	.21 .1180	.24 .0755	.24 .0755	.20 .1429	.21 .1240	.25 .0660	.25 .0600	.09 .5136	.05 .7372	1.00	
SM2	.27 .0456	.27 .0472	.32 .0159	.31 .0198	.31 .0198	.32 .0171	.29 .0341	.34 .0117	.27 .0471	-.27 .0386	.59 .0001	.00 .9905	1.00

TABLE 2-5 CORRELATIONS AND SIGNIFICANCE LEVELS AT FLOWERING

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	GROW	YLD	SM1	SM2
AVI	1.00												
DVI	1.00 .0001	1.00											
LAI	.85 .0001	.81 .0001	1.00										
GVI	.99 .0001	.99 .0001	.86 .0001	1.00									
KVI	.99 .0001	.99 .0001	.86 .0001	1.00 .0001	1.00								
TVI6	.91 .0001	.88 .0001	.98 .0001	.92 .0001	.92 .0001	1.00							
TVI7	.94 .0001	.91 .0001	.97 .0001	.93 .0001	.93 .0001	.99 .0001	1.00						
PVI6	.97 .0001	.98 .0001	.81 .0001	.99 .0001	.99 .0001	.87 .0001	.88 .0001	1.00					
PVI7	1.00 .0001	1.00 .0001	.81 .0001	.99 .0001	.99 .0001	.88 .0001	.91 .0001	.98 .0001	1.00				
GROW	-.03 .7629	-.02 .8459	-.15 .1302	-.02 .8315	-.02 .8315	-.09 .3623	-.09 .3569	-.01 .9098	-.02 .8447	1.00			
YIELD	.11 .2545	.08 .4038	.31 .0015	.14 .1586	.14 .1586	.30 .0027	.26 .0105	.10 .3056	.08 .4030	.24 .0154	1.00		
SM1	.29 .0033	.30 .0028	.19 .0530	.25 .0121	.25 .0121	.21 .0390	.24 .0155	.24 .0182	.30 .0028	-.40 .0001	-.26 .0096	1.00	
SM2	.23 .0232	.21 .0402	.33 .0010	.22 .0260	.22 .0260	.32 .0010	.31 .0016	.18 .0686	.21 .0401	-.03 .7389	.48 .0001	.12 .2304	1.00

SEP 18 1979

TABLE 2-6 CORRELATIONS AND SIGNIFICANCE LEVELS AT RIPENING

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	GROW	YLD	SM1	SM2
AVI	1.00												
DVI	.99 .0001	1.00											
LAI	.94 .0001	.91 .0001	1.00										
GVI	.99 .0001	.99 .0001	.94 .0001	1.00									
KVI	.99 .0001	.99 .0001	.94 .0001	1.00 .0001	1.00								
TVI6	.96 .0001	.94 .0001	.79 .0001	.97 .0001	.97 .0001	1.00							
TVI7	.98 .0001	.97 .0001	.98 .0001	.97 .0001	.97 .0001	.98 .0001	1.00						
PVI6	.96 .0001	.97 .0001	.90 .0001	.99 .0001	.99 .0001	.93 .0001	.93 .0001	1.00					
PVI7	.99 .0001	1.00 .0001	.91 .0001	.99 .0001	.99 .0001	.94 .0001	.97 .0001	.97 .0001	1.00				
GROW	-.58 .0001	-.58 .0001	-.56 .0001	-.56 .0001	-.56 .0001	-.57 .0001	-.59 .0001	-.52 .0001	-.57 .0001	1.00			
YIELD	.01 .8820	-.01 .8936	.08 .1742	-.02 .7395	-.02 .7395	.04 .4707	.06 .2927	-.05 .3153	-.01 .8835	-.09 .1064	1.00		
SM1	-.21 .0002	-.23 .0001	-.13 .0257	-.19 .0009	-.19 .0009	-.16 .0066	-.21 .0003	-.17 .0023	-.23 .0001	.13 .0266	-.09 .1037	1.00	
SM2	.37 .0001	.34 .0001	.47 .0001	.37 .0001	.37 .0001	.44 .0001	.42 .0001	.34 .0001	.34 .0001	-.33 .0001	.39 .0001	-.06 .3162	1.00

TABLE 2-7 CORRELATIONS AND SIGNIFICANCE LEVELS AT HARVEST

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	YLD	SM1	SM2
AVI	1.00											
DVI	.93 .0001	1.00										
LAI	.81 .0001	.81 .0001	1.00									
GVI	.91 .0001	.96 .0001	.89 .0001	1.00								
KVI	.91 .0001	.96 .0001	.89 .0001	1.00 .0001	1.00							
TVI6	.83 .0001	.87 .0001	.98 .0001	.93 .0001	.93 .0001	1.00						
TVI7	.95 .0001	.96 .0001	.90 .0001	.95 .0001	.95 .0001	.93 .0001	1.00					
PVI6	.72 .0001	.90 .0001	.76 .0001	.92 .0001	.92 .0001	.84 .0001	.82 .0001	1.00				
PVI7	.92 .0001	.99 .0001	.78 .0001	.95 .0001	.95 .0001	.84 .0001	.93 .0001	.90 .0001	1.00			
YIELD	-.41 .0001	-.38 .0001	-.46 .0001	-.42 .0001	-.42 .0001	-.47 .0001	-.45 .0001	-.35 .0001	-.42 .0001	1.00		
SM1	-.17 .0078	-.18 .0059	-.03 .6911	-.19 .0046	-.19 .0046	-.08 .2150	-.16 .0205	-.14 .0321	-.19 .0317	.03 .6101	1.00	
SM2	-.05 .4189	-.06 .3861	-.18 .0059	-.13 .0606	-.13 .0606	-.18 .0060	-.12 .0682	-.10 .1318	-.04 .5246	.43 .0001	.08 .2536	1.00

SEP 18 1979

plant density and yield, and two soil moisture estimates including surface and subsurface soil moisture at the seven growth stage intervals.

The level of correlation among the VI's was high throughout the growth cycle. These relationships reached a maximum at stem extension and heading. The correlation between VI's based on band 6 to those VI's based on band 7 were lower when compared to correlations of the VI's based on the same near infrared band. The LAI, TVI6, and PVI6 use band 6 in their calculations, while the AVI, DVI, GVI, KVI, TVI7, and PVI7 use band 7. Generally, the LAI and TVI6 consistently produced a stronger relationship to yield at each of the growth stage intervals.

The relationship between the VI's and yield and the other ground observed parameters were at approximately the same level of correlation due to the high inter-correlation between the VI's. The correlations did vary between these variables, but they were not significantly different. The relationship between yield and the VI's was not expected to strengthen until stem extension and peak until heading. The average correlation coefficients between the VI's and yield were .36 at stem extension, .58 at heading, and .17 at flowering. Correlation coefficients between yield and the VI's at planting and harvest were negative and averaged -.31 and -.42, respectively.

Correlation coefficients between yield and the VI's at tillering were negative and averaged -.26. The increase in the plant biomass reduced the correlation coefficients found at tillering. The VI's were no longer measuring the reflectance from the soils primarily, due in part to the level of moisture, but also beginning to measure the reflectance of the plant canopy.

Correlation coefficients between yield and the VI's at ripening varied from being slightly negative to being slightly positive. The correlation coefficients averaged .01 and indicated a weak relationship between yield and the VI's.

2.2.2.2 Effect of Wheat Type. The intentions of this analysis were to compute correlation tables similar to those presented earlier, independently for spring wheat and winter wheat observations at the stem extension, heading and flowering growth stage intervals. The lack of a sufficient number of observations for each wheat type at each growth stage interval prevented a complete analysis across the entire crop calendar. The data did support analysis for both wheat types at heading, but not at stem extension and flowering.

Stratification by wheat type did not affect the relationship between yield and the VI's at heading (refer to Appendix B for Correlation Tables). The average correlation coefficient was

SEP 18 1979

.57 for spring wheat and .61 for winter wheat, compared to an average correlation coefficient of .58 for the entire data set, irrespective of wheat type.

Stratification by wheat type did not affect the relationship between yield and the VI's at flowering. The average correlation coefficient at flowering was .19 for spring wheat compared to .18 for all wheat. Analysis could not be conducted independently for winter wheat due to an insufficient number of observations.

Stratification by wheat type at stem extension did have some effect on the relationship between yield and the VI's. The average correlation coefficient was .48 for winter wheat compared to .36 for all wheat, an increase of 33 percent.

2.2.2.3 Effect of Field Size. The purpose of increasing the minimum field size was to reduce the effects of border or edge pixels on the VI statistical mean computed over each field. The average field size for fields greater than 30 pixels was 57 pixels, for fields greater than 40 pixels the average size was 78 pixels and for fields greater than 50 pixels the average size was 91 pixels. The average size for all fields in the data set was 41 pixels, or approximately 45 acres.

Generally, the field size constraint reduced the strength of the relationship between yield and the VI's at stem extension (refer to Appendix C for Correlation Tables). The average correlation coefficient between yield and the VI's was .53, .23, and .14 for the 30, 40 and 50 pixel field size constraints, respectively. This compares with the average correlation coefficient of .36 for all the fields in the data set. The relationship between yield and the VI's is relatively low and inconsistent during the stem extension period.

During heading, the effect of the field size constraints was to strengthen the relationship between yield and the VI's. The average correlation coefficient increased to .73, .72 and .66 for the 30, 40 and 50 pixel field size contraints, respectively. This compares with the average correlation coefficient of .58 at heading based on all the fields in the data set. The increase in the correlation coefficient after imposing a 30 pixel field size constraint is hypothesized to be due to the effect of reducing the number of edge or border pixels thereby reducing their effect on the VI statistical mean for each field. Though analysts purposely tried to avoid defining fields containing border pixels, in some cases the small size of some fields prevented the definitions of fields containing entirely pure wheat pixels. The relationship between yield and the VI's was relatively high and stable during heading.

The effect of increasing the field size constraint during flowering was similar to that found at heading, although the relationship between yield and the VI's was weak. The average

correlation coefficient was .21, .39, and .33 for the 30, 40 and 50 pixel field size constraints, respectively. This compares with the average correlation coefficient at flowering of .17 based on all the fields in the data set. Similiarly, as found during heading, reducing the effect of border pixels improved the relationship between yield and the VI's.

2.2.2.4 Effect of APU Location. The effect of segment location on the relationship between yield and the VI's was also investigated. The field level data was stratified according to its location with respect to the agrophysical units (APU) identified in Montana and North Dakota (Figure 1-1). The purpose of computing the correlation coefficients by APU were to reduce the effects of soils and climate on the relationship between the VI's and yield. There were five APU's identified in the two states including APU 19, 20, 21, 22 and 104. APU 104 was not included in the analysis due to the low segment acquisition rate experienced within this region in Montana.

It was originally intended to compute correlation tables, independently for each APU at the stem extension, heading and flowering growth stage intervals. Again, the low percentage of data at these growth stages prevented a complete and thorough analysis. Correlations were only computed at flowering for APU 19 and 20, at heading and flowering for APU 21, and at stem extension and flowering for APU 22 (refer to Appendix D for Correlation Tables). A comparison of the correlation coefficients at the APU level to those computed without respect to stratification, provided the basis for analysis.

Only one APU contained sufficient data[3/] to support correlation analysis at stem extension. The average correlation coefficient at stem extension in APU 22 was .67, compared to .36 for the entire data set, an increase of 86 percent. Definite conclusions cannot be identified due to the lack of sufficient data at each of the other APU's.

Only two APU's contained a sufficient number of observations at heading to conduct the analysis. The average correlation coefficients at heading in APU's 21[4/] and 22[4/] were .45 and .52, respectively. This compares with an average correlation coefficient at heading of .58 for the entire data set. In this case, APU location had a slight negative affect on the relationship between yield and the VI's. Collectively, the observations at heading in the other APU's supported a strong correlation between yield and the VI's.

Three APU's contained a sufficient number of observations

3/ APU 22 contained 17 observations during stem extension

4/ APU 21 contained 21 observations, while APU 22 contained 23 observations.

at flowering to conduct the analysis. The average correlation coefficients at flowering in APU's 19[5/], 20[5/] and 21[5/] were .45, .13 and -.18, respectively. This compares with an average correlation coefficient at flowering of .17 for the entire data set. Although the relationship between yield and the VI's is relatively weak at flowering, the stratification by APU did little to strengthen this relationship. The variation between yield and the VI's was so great during this period that the relationship was negative in APU 21 and positive in APU's 19 and 20.

Definite conclusions cannot be drawn by this analysis due to the low volume of data collected in each of the APU's during the stem extension, heading and flowering growth stage intervals. There is an indication that stratification of the data by APU has little effect on the relationship between yield and the VI's. The relationship remained strongest at heading in each APU.

2.2.3 Yield and Soil Moisture. Surface and subsurface soil moisture estimates were computed from the Two Layer Soil Moisture Model. This section presents the correlation analysis results between surface and subsurface soil moisture, the VI's, and the ground observed data.

Subsurface soil moisture showed a stronger relationship to yield than was found with surface soil moisture. Figures 2-9 through 2-15 show the relationship between subsurface soil moisture and yield. The relationship between yield and subsurface soil moisture peaked at heading producing a correlation coefficient of .59. The relationship at other growth stage intervals was relatively strong and averaged above .45 except at stem extension when it dropped to .15. (Refer to Tables 2-1 through 2-7.) The soil moisture estimates from the Two Layer Soil Moisture Model correlated reasonably well to yield.

2.2.4 Plant Density, Plant Height and VI's. Tillering and stem extension were the only growth stage intervals in which meaningful relationships between plant height, plant density and each of the VI's were possible. Therefore, the analysis was limited to these growth stage intervals. The methods of recording the ground observed data was the principle obstacle to this analysis. After stem extension plant density reached its peak of code 5 indicating a range of 80 to 100 percent ground cover, and did not vary during the remainder of the growing season. A similar situation was found with plant height, reaching its peak after stem extension and not varying during the remainder of the growing season.

5/ APU 19, 20 and 21 contained 18, 21 and 16 observations, respectively.

FIGURE 2-9 YIELD VS. SUBSURFACE SOIL MOISTURE AT PLANTING

PLOT OF YIELD*SOILMO2 LEGEND: A = 1 OBS, B = 2 OBS, ETC.

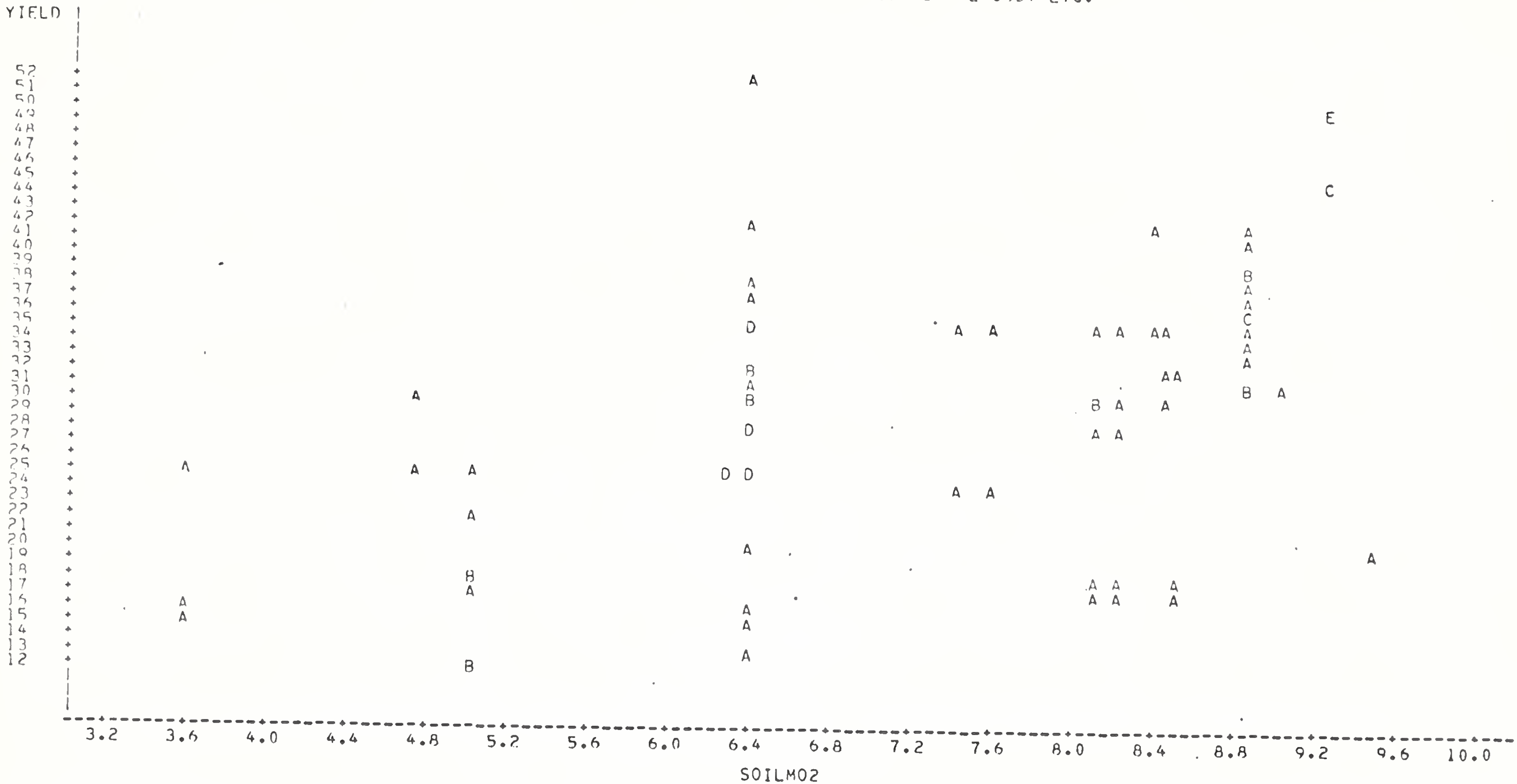


FIGURE 2-10 YIELD VS. SUBSURFACE SOIL MOISTURE AT TILLERING

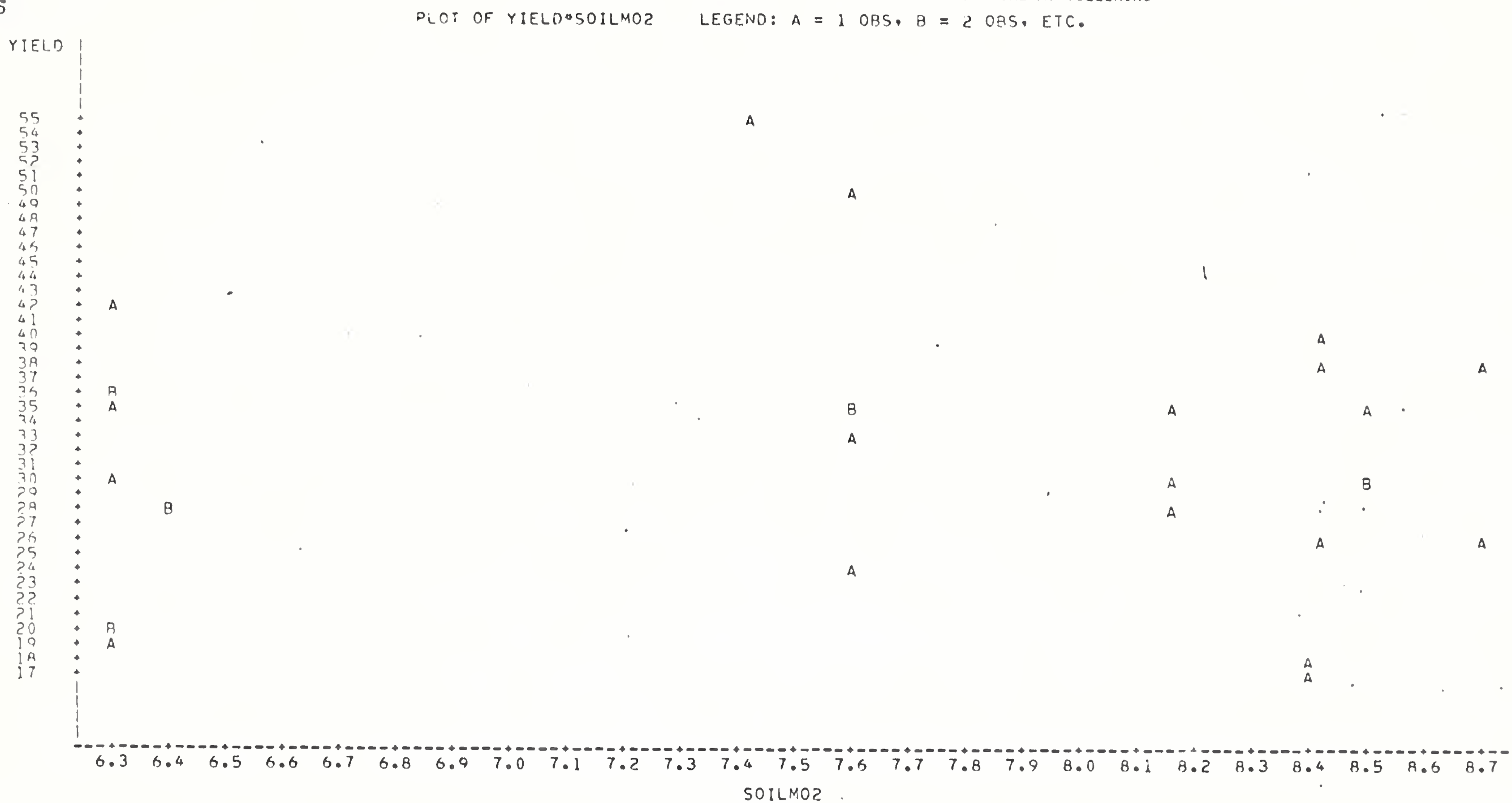


FIGURE 2-11 YIELD VS. SUBSURFACE SOIL MOISTURE AT STEM EXTENSION

PLOT OF YIELD*SOILMO2   LEGEND: A = 1 OBS. B = 2 OBS, ETC.

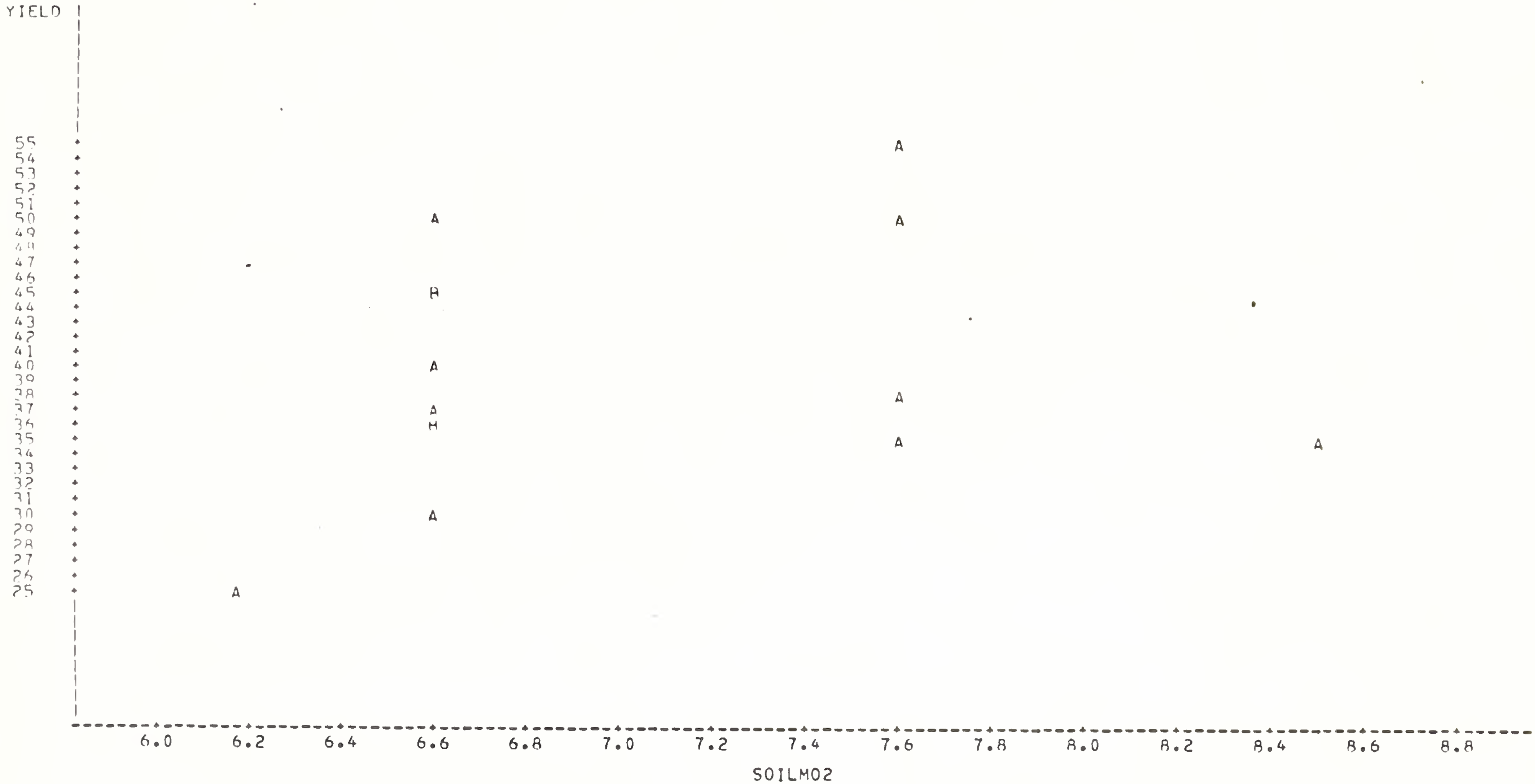


FIGURE 2-12 YIELD VS. SUBSURFACE SOIL MOISTURE AT HEADING

PLOT OF YIELD*SOILMO2   LEGEND: A = 1 OBS, B = 2 OBS, ETC.

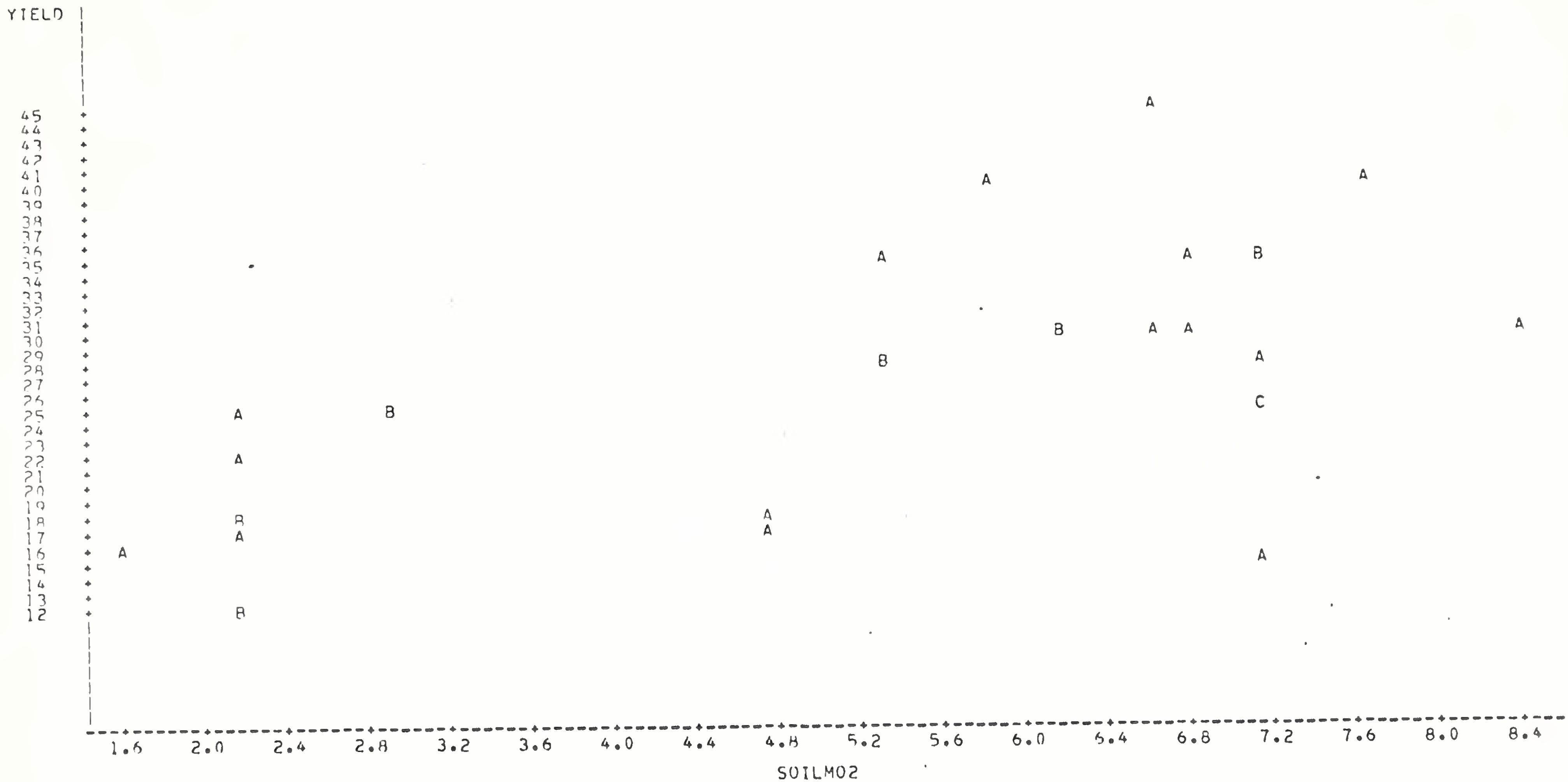
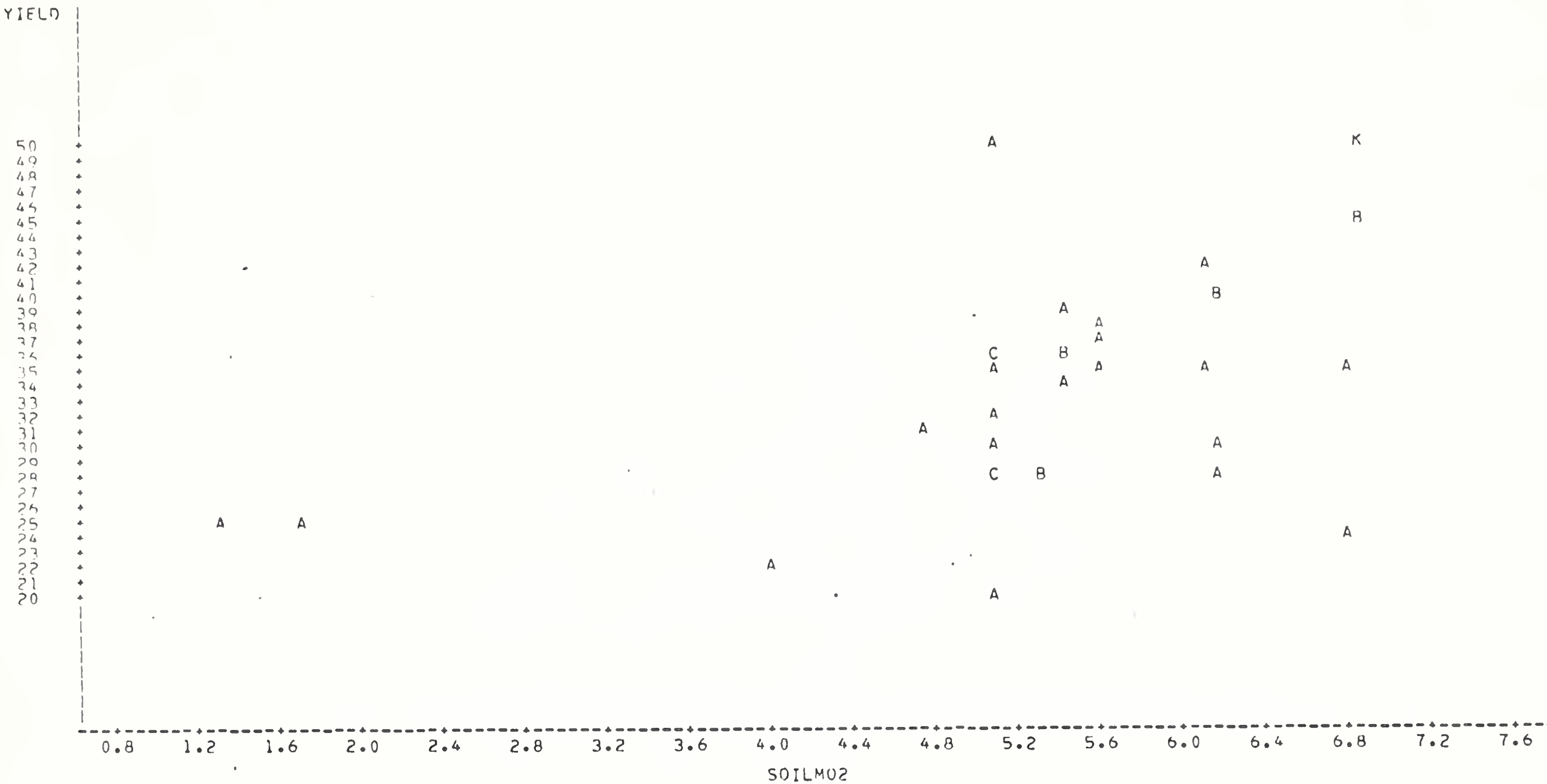


FIGURE 2-13 YIELD VS, SUBSURFACE SOIL MOISTURE AT FLOWERING

PLOT OF YIELD*SOILMO2   LEGEND: A = 1 OBS, B = 2 OBS, ETC.



SEP 18 1979

FIGURE 2-14 YIELD VS. SUBSURFACE SOIL MOISTURE AT RIPENING

PLOT OF YIELD*SOILMO2 LEGEND: A = 1 OBS, B = 2 OBS, ETC.

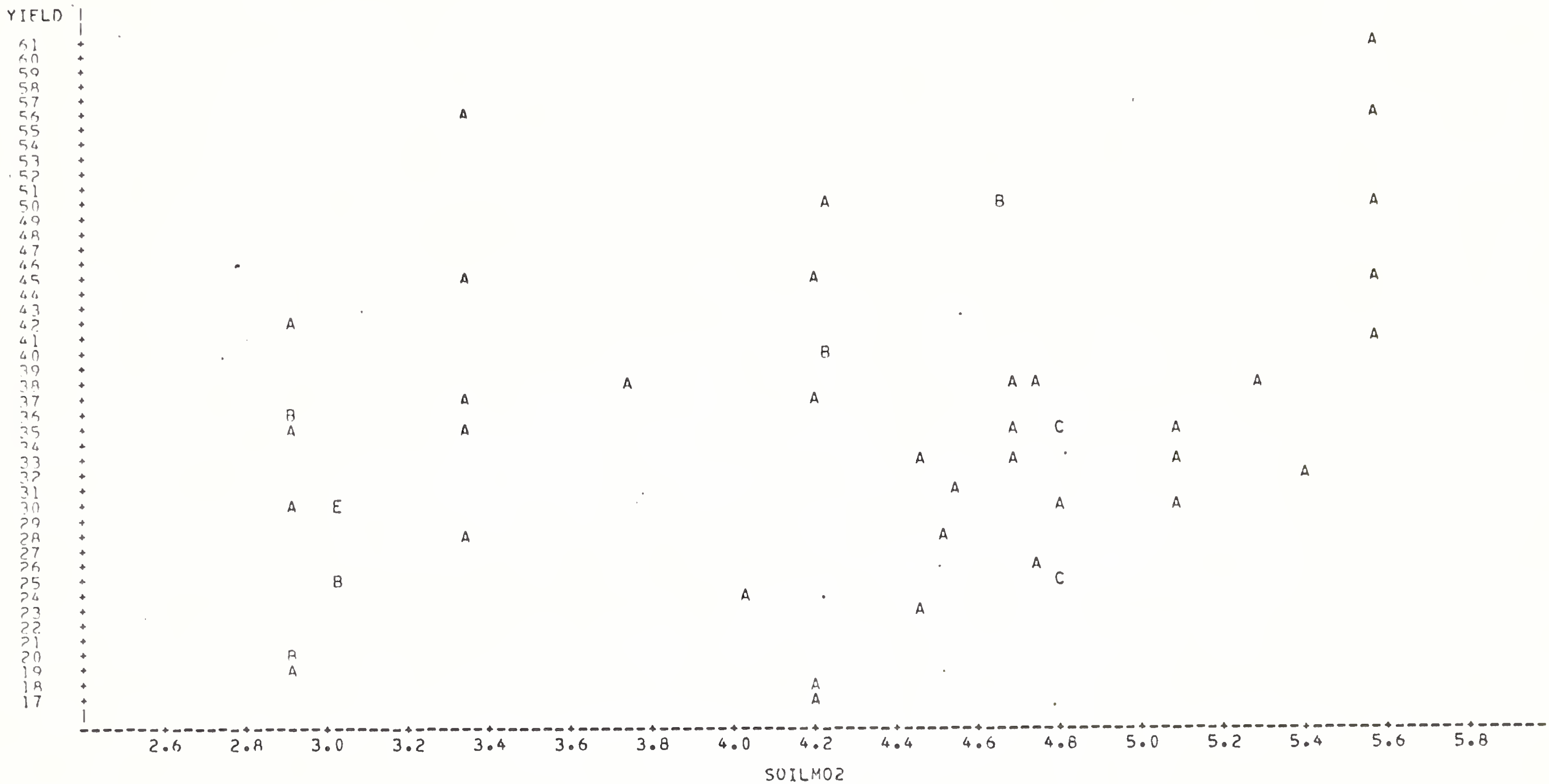
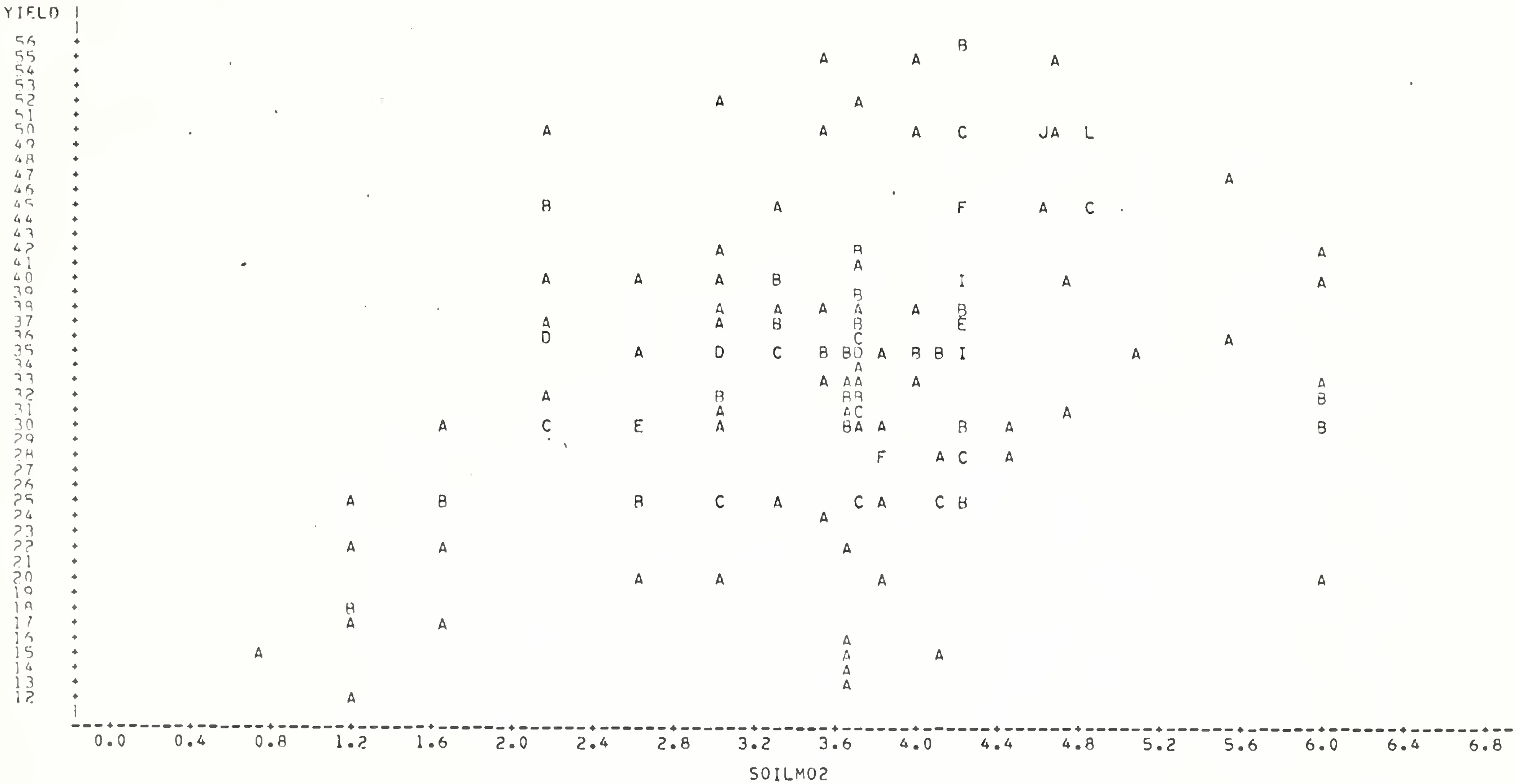


FIGURE 2-15 YIELD VS. SUBSURFACE SOIL MOISTURE AT HARVEST

PLOT OF YIELD*SOILMO2   LEGEND: A = 1 OBS, B = 2 OBS, ETC.



2.2.4.1 Plant Density and VI's. The relationship between plant density and the VI's was strong at both tillering and stem extension. The average correlation coefficients between the VI's and plant density were .49 and .67 at tillering and stem extension, respectively (Tables 2-2 and 2-3). The correlation coefficients ranged from a high of .51 for the KVI to a low of .45 for the LAI at tillering and from a high of .71 for the TVI6 to a low of .65 for the DVI at stem extension. The VI's measured plant density similarly.

2.2.4.2 Plant Height and VI's. The relationship between plant height and the VI's was also strong at tillering and stem extension. The average correlation coefficient between the VI's and plant height were .66 and .81 at tillering and stem extension, respectively (Tables 2-2 and 2-3). The correlation coefficients at tillering ranged from a high of .69 for the KVI to a low of .63 for the TVI7, and at stem extension ranged from a high of .84 for the DVI to a low of .76 for the LAI. The VI's measured plant height similarly.

PART 3.0 REGRESSION ANALYSIS RESULTS

3.1 OVERVIEW

The purpose of the multiple regression analysis was to identify functional relationships between a set of independent variables including the VI's, soil moisture and a number of interactive terms and the dependent variables including plant density, plant height and yield[7]. This analysis identified the times in the growing year when significant relationships to plant density, plant height and yield occurred. Additionally, the analysis identified those variables that are functionally related to the set of dependent variables and the relative strength of these relationships.

A stepwise regression procedure was implemented for each VI at each of the seven growth stage intervals. A table listing the independent variables used in the regression analysis is presented as Appendix E. The VI's were never jointly analyzed in a regression, but rather were individually regressed against the set of dependent variables. The results of this analysis are presented in the following sections.

3.2 RELATIONSHIPS TO YIELD

3.2.1 Planting. The VI's did not enter into the regression relationship defined at planting (Table 3-1). Instead, subsurface soil moisture raised to the fourth power was the only significant variable entering into the regression relationship. A coefficient of determination of .32 and a standard deviation of 8.12 indicated a relatively weak relationship to yield. The relative strength of the relationship at planting was expected, because it is too early in the growing season to accurately explain final yield. Although the relationship was weak at planting, it was expected that subsurface soil moisture would have some relationship to final yield at planting.

3.2.2 Tillering. The strength of the relationship at tillering was also weak and produced an average coefficient of determination and standard deviation for all the VI's of .28 and 8.40, respectively (Table 3-2). The independent variables entering consistently into the regression equations were a dummy variable[8] differentiating between spring and winter wheat, subsurface soil moisture raised to the third power, the VI multiplied by the sum of surface and subsurface soil moisture, and the VI added to subsurface

---

7/ Since there was a perfect correlation between the KVI and the GVI (due to sun angle and haze correction) as reported in Part 2.0, the GVI was deleted from the list of VI's analyzed by regression analysis. The results for both VI's would have been similar.

8/ A dummy variable is used to measure the difference between factors that cannot easily be quantified. In this case the factor being measured is the effect of wheat type on final yield.

TABLE 3-1 YIELD REGRESSION RELATIONSHIP AND ASSOCIATED STATISTICS FOR EACH VI AT PLANTING

VI	N[1]	R^2[2]	STD DEV[3]	B-VALUE[4]	STD ERROR[5]	F-VALUE[6]	PROB > F[7]
ALL VI's	88	.32	8.12	-	-	40.22	.0001
VARIABLES							
Intercept	-	-	-	21.862	-	-	-
SM2FO	-	-	-	0.002	.0004	40.22	.0001

---

[1]"N" is the number of observations.

[2]"R^2" is the coefficient of determination indicating the amount of variation in the dependent variable (yield) explained by the independent variable(s). "R^2" ranges from 0.00 to 1.00.

[3]"STD DEV" is the average deviation between the observed and estimated yield.

[4]"B-VALUES" are the coefficients or weights applied to each of the independent variables. Additionally, the intercept is also listed under "B-VALUE."

[5]"STD ERROR" is the standard error of the B-Values.

[6]"F-VALUE" is used to test whether the linear relationship is significant. Additionally, it is used to test whether a variable meets the significance criteria and should be included in the model (partial F-Test). The F-Value is the ratio of the regression mean square to the error mean square.

[7]"PROB >F" is the significance probability of the F-Value.

TABLE 3-2 YIELD REGRESSION RELATIONSHIP AND ASSOCIATED STATISTICS FOR EACH VI AT TILLERING

VI	N	R^2	STD DEV	B-VALUE	STD ERROR	F-VALUE	PROB >F
AVI	196	.24	8.66	-	-	19.97	.0001
VARIABLES							
Intercept	-	-	-	33.46	-	-	-
Wheat	-	-	-	-3.80	1.452	6.86	.0095
SM1CU	-	-	-	-6.54	2.258	8.47	.0040
SM2CU	-	-	-	0.02	0.003	45.06	.0001
DVI	196	.29	8.35	-	-	20.06	.0001
VARIABLES							
Intercept	-	-	-	19.61	-	-	-
Wheat	-	-	-	-3.79	1.430	7.04	.0086
SM2CU	-	-	-	0.02	0.003	49.61	.0001
DVIMSM3	-	-	-	-0.25	0.056	21.43	.0001
DVIASM2	-	-	-	1.82	0.426	18.20	.0001
LAI	196	.30	8.30	-	-	20.89	.0001
VARIABLES							
Intercept	-	-	-	18.00	-	-	-
Wheat	-	-	-	-3.80	1.450	6.87	.0095
SM2CU	-	-	-	0.02	0.003	27.53	.0001
LAIMSM3	-	-	-	-0.32	0.066	23.52	.0001
LAIASM2	-	-	-	2.26	0.511	19.64	.0001
KVI	196	.30	8.33	-	-	20.26	.0001
VARIABLES							
Intercept	-	-	-	14.33	-	-	-
Wheat	-	-	-	-3.80	1.429	7.08	.0084
SM2CU	-	-	-	0.02	0.003	36.67	.0001
KVIMSM3	-	-	-	-0.39	0.082	22.25	.0001
KVIASM2	-	-	-	2.73	0.628	18.95	.0001
TVI6	196	.27	8.49	-	-	23.44	.0001
VARIABLES							
Intercept	-	-	-	19.35	-	-	-
Wheat	-	-	-	-2.97	1.38	4.62	.0328
SOILMO2	-	-	-	8.60	1.27	46.20	.0001
TVIMSM3	-	-	-	-5.25	1.24	18.03	.0001
TVI7	196	.25	8.57	-	-	21.69	.0001
VARIABLES							
Intercept	-	-	-	10.79	-	-	-
Wheat	-	-	-	-2.37	1.40	2.87	.0919
TVIMSM3	-	-	-	-4.81	1.23	15.26	.0001
TVIASM2	-	-	-	7.21	1.04	47.95	.0001
PVI6	196	.31	8.24	-	-	21.81	.0001
VARIABLES							
Intercept	-	-	-	4.00	-	-	-
Wheat	-	-	-	-4.12	1.38	8.98	.0031
PVIMSM3	-	-	-	-0.39	0.09	17.09	.0001
PVIASM1	-	-	-	-2.86	0.53	28.99	.0001
PVIASM2	-	-	-	5.53	0.69	63.46	.0001
PVI7	196	.30	8.28	-	-	27.76	.0001
VARIABLES							
Intercept	-	-	-	0.39	-	-	-
Wheat	-	-	-	-3.61	1.39	6.71	.0103
PVIMSM3	-	-	-	-0.81	0.09	79.49	.0001
PVIASM2	-	-	-	5.68	0.70	65.42	.0001

soil moisture. There was minimal variation in the variables entering into the yield relationship when using each VI. The similarity of the regression relationships for each VI was expected due to the high correlation among the VI's. Again, soil moisture proved to be an important variable in explaining the variation in yield. The interaction between the VI's and soil moisture also proved to be extremely significant in explaining the variation in wheat yield.

Historically, winter wheat because of its longer growing season along with physiologically based differences produces a higher yield when compared to the yields produced by spring wheat. The regression relationship defined at tillering depicted this relationship. A code variable was defined to differentiate between wheat types with a value of one given to the winter wheat fields and a value of two given to the spring wheat fields. The negative coefficient preceding the wheat type variable indicates that at a specific growth stage given a value of a VI, the yield of a field planted to spring wheat will be less than the yield planted to a field of winter wheat.

3.2.3 Stem Extension. The relationship between yield and the independent variables improved at stem extension. The coefficient of determination and the standard deviation for all the VI's averaged .41 and 5.87, respectively (Table 3-3). The standard deviation ranged from a low of 5.51 for the LAI to a high of 6.32 for the TVI6. The independent variables consistently entering into the regression equation for each VI were a dummy variable indicating the wheat type (i.e., winter or spring wheat), the VI multiplied by the sum of surface and subsurface soil moisture, and the VI multiplied by the growth stage within the stem extension interval. The LAI multiplied by subsurface soil moisture was the most significant variable found in the relationships defined for the TVI6 and TVI7. The VI multiplied by the growth stage was not significant in the case of the yield regression relationship defined for the LAI.

During stem extension the wheat plant is undergoing a significant amount of growth (Figure 1-2). Plant density within the fields is increasing at a maximum rate. The VI multiplied by the growth stage is understandably an important variable in explaining the variation in yield. This term adjusts the VI for the growth stage within the stem extension interval. For example, a VI of 25 at growth stage 6.0 would indicate a greater potential yield when compared to the same VI at growth stage 8.0.

The interaction between the VI and surface and subsurface soil moisture also proved to be significant. In fact, in most of the relationships this term was the most significant variable to yield (refer to significance levels for each of the independent variables).

The dummy variable differentiating between wheat types proved to be significant at stem extension, as was the case at tillering.

TABLE 3-3 YIELD REGRESSION RELATIONSHIP AND ASSOCIATED STATISTICS FOR EACH VI AT STEM EXTENSION

VI	N	R^2	STD DEV	B-VALUE	STD ERROR	F-VALUE	PROB >F
AVI	31	.46	5.68	-	-	7.68	.0007
VARIABLES							
Intercept	-	-	-	39.57	-	-	-
Wheat	-	-	-	-8.32	2.53	10.84	.0028
AVIMSM3	-	-	-	0.14	0.04	12.53	.0015
AVIMGRO	-	-	-	-0.08	0.03	7.69	.0100
DVI	31	.44	5.79	-	-	7.10	.0011
VARIABLES							
Intercept	-	-	-	36.78	-	-	-
Wheat	-	-	-	-8.33	2.59	10.35	.0034
DVIMSM3	-	-	-	0.11	0.03	11.64	.0021
DVIMGRO	-	-	-	-0.53	0.02	6.40	.0176
LAI	31	.49	5.51	-	-	8.78	.0003
VARIABLES							
Intercept	-	-	-	35.71	-	-	-
Wheat	-	-	-	-8.98	2.53	12.59	.0015
LAIMSM2	-	-	-	0.17	0.04	15.82	.0005
LAIMGRO	-	-	-	-0.07	0.02	8.40	.0074
KVI	31	.43	5.82	-	-	6.90	.0013
VARIABLES							
Intercept	-	-	-	35.12	-	-	-
Wheat	-	-	-	-8.34	2.63	10.08	.0039
KVIMSM3	-	-	-	0.16	0.05	11.56	.0021
KVIMGRO	-	-	-	-0.07	0.03	6.20	.0193
TVI6	31	.31	6.32	-	-	6.26	.0057
VARIABLES							
Intercept	-	-	-	10.46	-	-	-
Wheat	-	-	-	-6.33	2.60	5.94	.0214
TVI6MSM3	-	-	-	3.88	1.44	7.23	.0119
TVI7	31	.37	6.02	-	-	8.33	.0014
VARIABLES							
Intercept	-	-	-	12.02	-	-	-
Wheat	-	-	-	-5.98	2.47	5.86	.0222
TVI7SM3	-	-	-	4.31	1.31	10.84	.0027
PVI6	31	.38	6.07	-	-	5.64	.0039
VARIABLES							
Intercept	-	-	-	35.06	-	-	-
Wheat	-	-	-	-8.36	2.76	9.18	.0053
PVI6MSM3	-	-	-	0.17	0.06	9.20	.0053
PVI6MGRO	-	-	-	-0.08	0.04	4.94	.0348
PVI7	31	.44	5.79	-	-	7.09	.0012
VARIABLES							
Intercept	-	-	-	36.70	-	-	-
Wheat	-	-	-	-8.31	2.59	10.31	.0034
PVI7MSM3	-	-	-	0.28	0.08	11.63	.0021
PVI7MGRO	-	-	-	-0.14	0.05	6.39	.0176

3.2.4 <u>Heading.</u> The relationship between yield and the independent variables peaked at heading. The coefficient of determination and the standard deviation between the observed and estimated yields averaged .57 and 5.75, respectively (Table 3-4). The standard deviation ranged from a low of 5.50 for the LAI to a high of 5.90 for the PVI6. For each VI, there was very little variation in the variables entering the regression relationship and the relative strength of the relationship at heading. This was due to the relatively high correlation among the VI's at heading.

The independent variable consistently entering into the regression equation for each VI and the variable which proved to be the most significant was the VI multiplied by subsurface soil moisture. The dummy variable differentiating between winter and spring wheat was also significant in the AVI, DVI and PVI7 yield relationships. The VI added to subsurface soil moisture also proved to be significant in the TVI6 and TVI7 relationships.

Figure 3-1 shows a comparison between the observed yields and the yields estimated by the LAI derived yield relationship. The term "LAIMSM2" (LAI multiplied by subsurface soil moisture) proved to be the only significant variable in the yield relationship defined at heading. The difference between the observed and estimated yields averaged 5.50 bushels/acre.

A significant improvement in the correlation coefficient at heading between the LAI and yield resulted from an increasing field size limitation (Section 2.2.2.3). This prompted further analysis investigating the effect of field size on the yield regression relationship.

The minimum field size limitations investigated were established at 30, 35, 40 and 45 pixels. For example, a 30 pixel minimum field size limitation prevented any fields less than 30 pixels in size from entering the yield regression analysis.

The analyses identified the "LAIMSM3" (LAI multiplied by the sum of surface and subsurface soil moisture) as the only significant variable explaining the variation in yield as a result of imposing the minimum field size limitations. The regression relationship improved significantly by implementing the field size constraints. The coefficient of determinations were .81, .80, .80 and .78 by imposing the 30, 35, 40 and 45 pixel field size constraints, respectively, compared to a .61 for all the field data. The standard deviations between the observed and estimated yields were 4.08, 4.18, 4.12 and 4.37 the 30, 35, 40 and 45 pixel field size constraints, respectively, compared to a 4.80 for all the field data. Figure 3-2 shows a comparison between the observed yields and the yields estimated by the LAI derived relationship for fields greater than 30 pixels in size.

The number of observations used to build the regression relationship after imposing the 30, 35 40 and 45 pixel field size constraints were 29, 26, 21 and 18 respectively, compared to 55 observations for the entire data set at heading. Over 45 percent of the fields in the data set were less than 30 pixels in size.

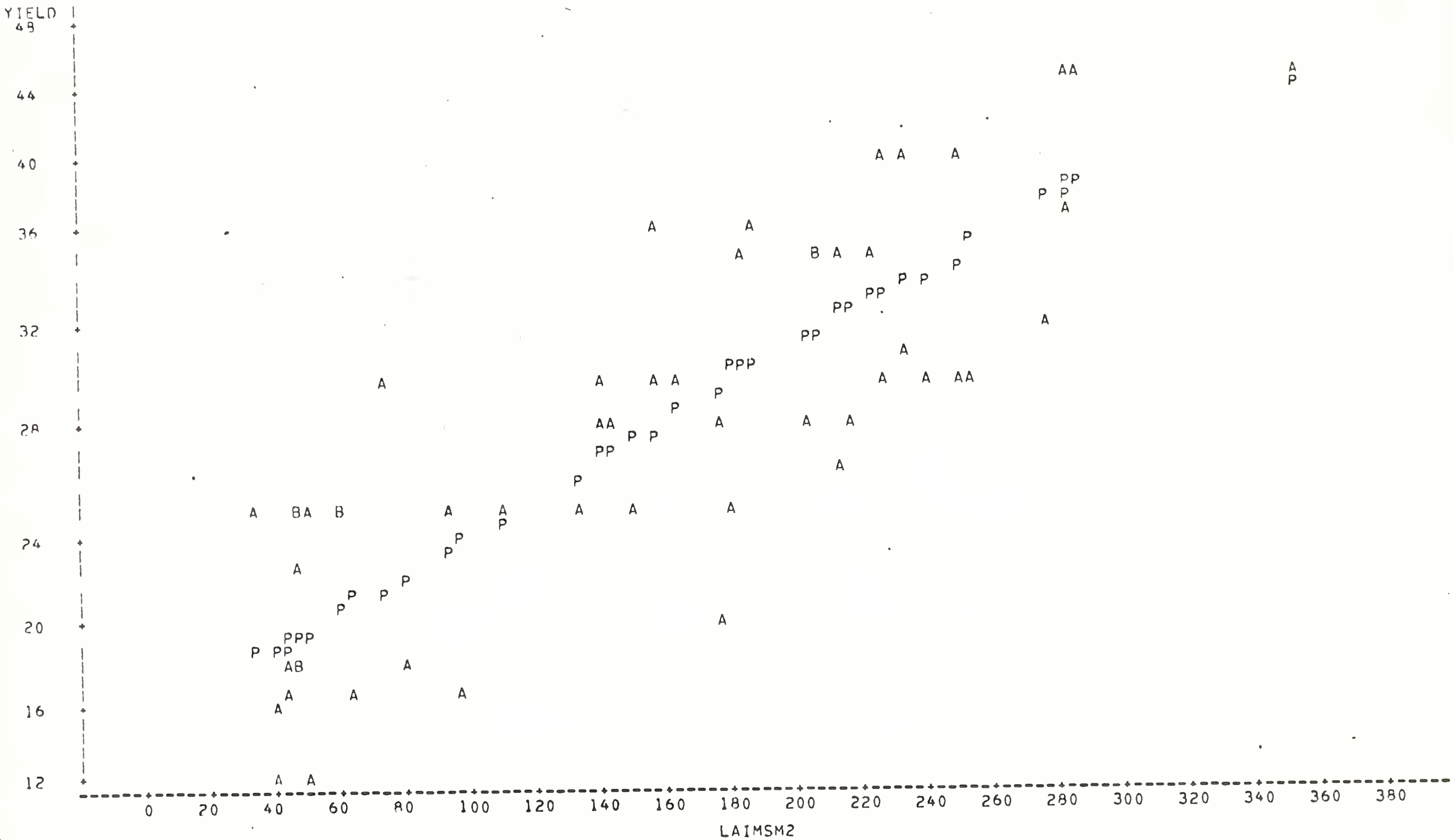
SEP 18 1979

TABLE 3-4 YIELD REGRESSION RELATIONSHIP AND ASSOCIATED STATISTICS FOR EACH VI AT HEADING

VI	N	R^2	STD DEV	B-VALUE	STD ERROR	F-VALUE	PROB >F
AVI	55	.57	5.81	-	-	34.41	.0001
VARIABLES							
Intercept	-	-	-	25.33	-	-	-
Wheat	-	-	-	-4.19	1.72	5.94	.0183
AVIMSM2	-	-	-	0.06	0.01	45.43	.0001
DVI	55	.56	5.84	-	-	33.71	.0001
VARIABLES							
Intercept	-	-	-	23.55	-	-	-
Wheat	-	-	-	-3.86	1.75	4.90	.0313
DVIMSM2	-	-	-	0.05	0.01	44.31	.0001
LAI	55	.61	5.50	-	-	81.68	.0001
VARIABLES							
Intercept	-	-	-	15.86	-	-	-
LAIMSM2	-	-	-	0.08	0.01	81.68	.0001
KVI	55	.55	5.83	-	-	66.06	.0001
VARIABLES							
Intercept	-	-	-	15.27	-	-	-
KVIMSM2	-	-	-	0.09	0.01	66.06	.0001
TVI6	55	.60	5.59	-	-	39.19	.0001
VARIABLES							
Intercept	-	-	-	36.94	-	-	-
TVIMSM2	-	-	-	17.61	3.13	31.59	.0001
TVIASM2	-	-	-	-18.52	3.79	23.93	.0001
TVI7	55	.58	5.73	-	-	36.11	.0001
VARIABLES							
Intercept	-	-	-	23.16	-	-	-
TVIMSM2	-	-	-	10.18	1.97	26.76	.0001
TVIASM2	-	-	-	-8.03	2.10	14.57	.0004
PVI6	55	.55	5.90	-	-	64.03	.0001
VARIABLES							
Intercept	-	-	-	15.09	-	-	-
AVIMSM2	-	-	-	0.10	.01	64.03	.0001
PVI7	55	.56	5.84	-	-	33.71	.0001
VARIABLES							
Intercept	-	-	-	23.56	-	-	-
Wheat	-	-	-	-3.86	1.75	4.90	.0313
AVIMSM2	-	-	-	0.14	0.02	44.31	.0001

FIGURE 3-1 OBSERVED AND ESTIMATED YIELDS VS. LAIMSM2 AT HEADING

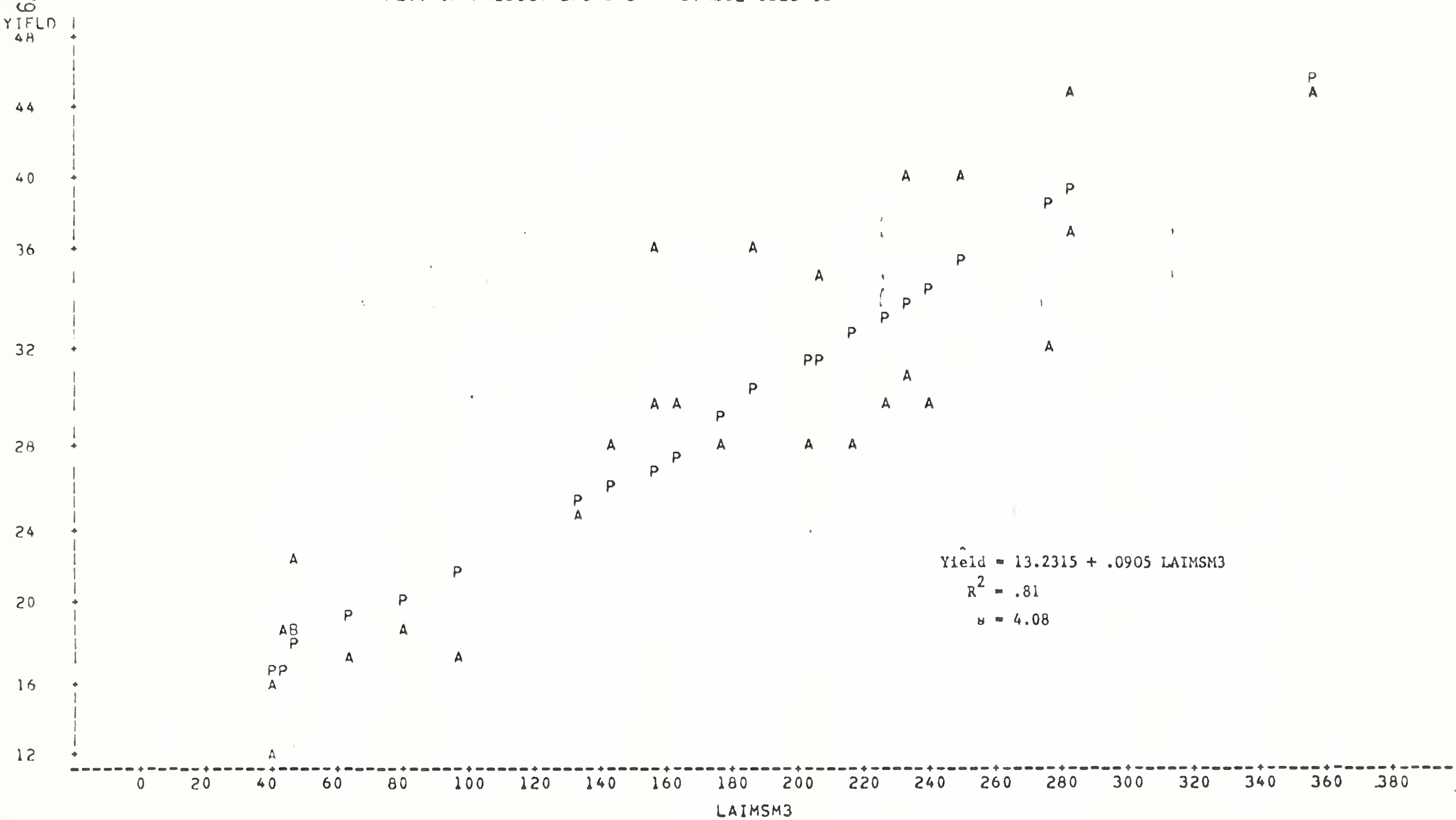
PLOT OF YIELD*LAIMSM2   LEGEND: A = 1 OBS, B = 2 OBS, ETC.
PLOT OF PREDICT*LAIMSM2   SYMBOL USED IS P



NOTE: 15 OBS HIDDEN

FIGURE 3-2 OBSERVED AND ESTIMATED YIELDS
vs. LAIMSM3 AT HEADING, FIELDS GREATER THAN 30 PIXELS

PLOT OF YIELD*LAIMSM3 LEGEND: A = 1 OBS, B = 2 OBS, ETC.
PLOT OF PREDICT*LAIMSM3 SYMBOL USED IS P



NOTE: 6 OBS HIDDEN

The improvement in the yield regression relationship at heading is believed to be due to the reduction in the effect border or edge pixels have on the VI statistical mean at the field level. That is, as the minimum field size is increased, the percentage of edge pixels to pure pixels is reduced. The analysis indicated that the yield relationship improved significantly after imposing the 30 pixel field size constraint, and remained stable as the field size constraint was increased to 35, 40 and 45 pixels. Further constraints could not be imposed due to an insufficient number of field observations greater than 45 pixels in size.

3.2.5 Flowering. The relationship between yield and the independent variables was also relatively strong at flowering. The coefficient of determination and the standard deviation between the observed and estimated yields averaged .62 and 6.00, respectively (Table 3-5). The standard deviation ranged from a low of 5.91 for the TVI6 to a high of 6.06 for the PVI6. There was a relatively small difference between the strength of the yield relationship defined at heading and flowering. In fact, the difference in the average standard deviation at heading and flowering was 0.25, a difference of 4 percent. Again, there was little variation in the independent variables entering the regression relationship and the relative strength of the relationship for each VI due to the high correlation among the VI's at flowering.

The sum of surface and subsurface soil moisture raised to the fourth power proved to be the most significant variable entering into the yield relationship for each VI. Other variables which proved to be significant were the VI multiplied by surface soil moisture, the dummy variable differentiating between wheat types and other soil moisture derived variables.

3.2.6 Ripening. At ripening, the relationship between yield and the independent variables was weakest and produced an average coefficient of determination and standard deviation between the observed and estimated yields of .26 and 9.52, respectively (Table 3-6). The standard deviation ranged from a low of 9.45 for the KVI to a high of 9.70 for the PVI7. There was little variation in the independent variables entering the regression relationship and the relative strength of the relationship for each VI at ripening.

Variables defined from subsurface soil moisture proved to be the most significant to yield. Those variables included the sum of surface and subsurface soil moisture raised to the fourth power, and the VI multiplied by subsurface soil moisture and subsurface soil moisture. Other variables which were significant included the code variable differentiating between wheat types and the VI multiplied by growth stage.

3.2.7 Harvest. The relationship between yield and the independent variables was stronger at harvest then was found at ripening. The coefficient of determination and the standard deviation between the observed and estimated yields averaged .42 and 7.36, respectively (Table 3-7). The standard deviation ranged from

TABLE 3-5 YIELD REGRESSION RELATIONSHIP AND ASSOCIATED STATISTICS FOR EACH VI AT FLOWERING

VI	N	R^2	STD DEV	B-VALUE	STD ERROR	F-VALUE	PROB >F
AVI	99	.61	6.04	-	-	29.69	.0001
VARIABLES							
Intercept	-	-	-	26.00	-	-	-
SM2SQ	-	-	-	-4.18	1.02	16.78	.0001
SM2FO	-	-	-	0.07	0.01	27.18	.0001
SM3CU	-	-	-	1.43	0.27	28.20	.0001
SM3FO	-	-	-	-0.19	0.03	34.51	.0001
AVIMSM1	-	-	-	0.48	0.25	3.49	.0648
DVI	99	.61	6.04	-	-	29.72	.0001
VARIABLES							
Intercept	-	-	-	26.00	-	-	-
SM2SQ	-	-	-	-4.18	1.02	16.85	.0001
SM2FO	-	-	-	0.07	0.01	26.74	.0001
SM3CU	-	-	-	1.43	0.27	28.29	.0001
SM3FO	-	-	-	-0.18	0.03	34.66	.0001
DVIMSM1	-	-	-	0.40	0.21	3.55	.0627
LAI	99	.64	5.97	-	-	27.31	.0001
VARIABLES							
Intercept	-	-	-	62.02	-	-	-
Wheat	-	-	-	-5.31	2.57	4.27	.0415
SOILMO2	-	-	-	-29.60	5.45	29.51	.0001
SM2SQ	-	-	-	5.90	0.93	40.52	.0001
SM3FO	-	-	-	-0.03	0.01	50.73	.0001
LAIMSM1	-	-	-	0.91	0.19	22.80	.0001
LAIMSM3	-	-	-	0.04	0.01	6.57	.0120
KVI	99	.61	6.05	-	-	29.50	.0001
VARIABLES							
Intercept	-	-	-	26.00	-	-	-
SM2SQ	-	-	-	-4.19	1.02	16.84	.0001
SM2FO	-	-	-	0.08	0.01	24.96	.0001
SM3CU	-	-	-	1.43	0.27	28.27	.0001
SM3FO	-	-	-	-0.19	0.03	34.09	.0001
KVIMSM1	-	-	-	0.66	0.38	3.10	.0816
TVI6	99	.63	5.91	-	-	26.68	.0001
VARIABLES							
Intercept	-	-	-	114.04	-	-	-
Wheat	-	-	-	-4.82	2.56	3.54	.0630
SM1FO	-	-	-	32.30	6.44	25.17	.0001
SM2SQ	-	-	-	5.79	0.91	39.98	.0001
SM3FO	-	-	-	-0.04	0.01	50.38	.0001
TVIMSM2	-	-	-	5.85	3.65	18.80	.0001
TVIASM2	-	-	-	-46.40	7.63	36.96	.0001
TVI7	99	.63	5.95	-	-	26.19	.0001
VARIABLES							
Intercept	-	-	-	102.45	-	-	-
Wheat	-	-	-	-4.83	2.58	3.52	.0639
SM2SQ	-	-	-	6.16	0.96	40.91	.0001
SM3FO	-	-	-	-0.04	0.01	50.60	.0001
TVIMSM1	-	-	-	32.33	6.32	26.12	.0001
TVIMSM2	-	-	-	10.89	2.36	21.26	.0001
TVIASM2	-	-	-	-40.74	6.93	34.56	.0001
PVI6	99	.61	6.06	-	-	29.40	.0001
VARIABLES							
Intercept	-	-	-	26.00	-	-	-
SM2SQ	-	-	-	-4.19	1.02	16.77	.0001
SM2FO	-	-	-	0.08	0.01	25.22	.0001
SM3CU	-	-	-	1.43	0.27	28.15	.0001
SM3FO	-	-	-	-0.19	0.03	33.86	.0001
PVIMSM1	-	-	-	0.70	0.41	2.91	.0912

TABLE 3-5 YIELD REGRESSION RELATIONSHIP AND ASSOCIATED STATISTICS FOR EACH VI AT FLOWERING (Continued)

VI	N	R^2	STD DEV	B-VALUE	STD ERROR	F-VALUE	PROB >F
PVI7	99	.61	6.04	-	-	29.72	.0001
VARIABLES							
Intercept	-	-	-	26.00	-	-	-
SM2SQ	-	-	-	-4.18	1.02	16.85	.0001
SM2FO	-	-	-	0.08	0.01	26.74	.0001
SM3CU	-	-	-	1.43	0.27	28.29	.0001
SM3FO	-	-	-	-0.19	0.03	34.66	.0001
PVIMSM1	-	-	-	1.05	0.56	3.55	.0628

TABLE 3-6 YIELD REGRESSION RELATIONSHIP AND ASSOCIATED STATISTICS FOR EACH VI AT RIPENING

VI	N	R^2	STD DEV	B-VALUE	STD ERROR	F-VALUE	PROB >F
AVI	293	.26	9.52	-	-	17.06	.0001
VARIABLES							
Intercept	-	-	-	5.76	-	-	-
Wheat	-	-	-	4.40	1.33	10.87	.0001
SOILMO2	-	-	-	-10.95	5.16	4.50	.0348
SM1SQ	-	-	-	-10.19	5.03	4.10	.0439
SM3FO	-	-	-	-0.004	0.001	11.02	.0010
AVIASM2	-	-	-	17.07	5.06	11.38	.0008
DVI	293	.27	9.51	-	-	14.86	.0001
VARIABLES							
Intercept	-	-	-	-236.08	-	-	-
GROWSTA	-	-	-	21.81	11.01	3.92	.0485
Wheat	-	-	-	4.05	1.32	9.37	.0024
SOILMO2	-	-	-	-22.21	8.21	7.31	.0073
DVIASM1	-	-	-	-0.004	0.001	11.34	.0009
DVIASM2	-	-	-	-9.03	4.10	4.86	.0283
LAI	293	.27	9.47	-	-	15.36	.0001
VARIABLES							
Intercept	-	-	-	32.10	-	-	-
LAI	-	-	-	11.07	5.04	4.82	.0289
Wheat	-	-	-	4.83	1.36	12.55	.0005
SOILMO2	-	-	-	-3.68	3.80	0.94	.3333
SM2SQ	-	-	-	1.21	0.57	4.51	.0345
SM3FO	-	-	-	-0.01	0.004	14.58	.0002
LAIMSM2	-	-	-	0.26	0.07	12.86	.0004
KVI	293	.28	9.45	-	-	15.67	.0001
VARIABLES							
Intercept	-	-	-	-356.71	-	-	-
KVI	-	-	-	35.53	10.13	12.31	.0005
GROWSTA	-	-	-	32.67	12.92	6.39	.0120
Wheat	-	-	-	4.03	1.30	9.64	.0021
SOILMO2	-	-	-	6.27	0.86	52.62	.0001
SM1CU	-	-	-	-12.92	5.76	5.03	.0257
SM3FO	-	-	-	-0.004	0.001	11.62	.0007
TVI6	293	.28	9.46	-	-	13.68	.0001
VARIABLES							
Intercept	-	-	-	-3810.52	-	-	-
GROWSTA	-	-	-	360.69	142.70	6.39	.0120
Wheat	-	-	-	4.54	1.37	10.96	.0010
SOILMO2	-	-	-	-3630.85	1484.98	5.98	.0150
SM2SQ	-	-	-	1.26	0.57	4.88	.0280
SM3FO	-	-	-	-0.01	0.004	13.15	.0003
TVIMSM2	-	-	-	26.52	13.31	3.97	.0472
TVIASM2	-	-	-	3600.75	1491.04	5.83	.0164
TVI7	293	.25	9.60	-	-	16.01	.0001
VARIABLES							
Intercept	-	-	-	142.54	-	-	-
Wheat	-	-	-	4.82	1.41	11.66	.0007
SOILMO2	-	-	-	-19.18	7.36	6.78	.0097
SM2SQ	-	-	-	0.99	0.57	2.97	.0862
SM3FO	-	-	-	-0.01	0.004	11.06	.0010
TVIMSM2	-	-	-	22.40	7.11	9.92	.0018

SEP 18 1979

TABLE 3-6 YIELD REGRESSION RELATIONSHIP AND ASSOCIATED STATISTICS FOR EACH VI AT RIPENING (Continued)

VI	N	R^2	STD DEV	B-VALUE	STD ERROR	F-VALUE	PROB >F
PV16	293	.27	9.47	-	-	21.08	.0001
VARIABLES							
Intercept	-	-	-	12.88	-	-	-
Wheat	-	-	-	3.35	1.28	6.86	.0093
SOILMO3	-	-	-	-6.09	3.21	3.61	.0583
SM3FO	-	-	-	-0.004	0.001	10.93	.0011
PV1ASM2	-	-	-	12.26	3.11	15.58	.0001
PV17	293	.23	9.70	-	-	21.66	.0001
VARIABLES							
Intercept	-	-	-	6.92	-	-	-
Wheat	-	-	-	3.42	1.33	6.64	.0105
SOILMO2	-	-	-	6.89	0.92	56.60	.0001
SM3FO	-	-	-	-0.004	0.001	11.42	.0008
PVIASM3	-	-	-	-0.52	0.14	13.10	.0003

SEP 18 1979

TABLE 3-7 YIELD REGRESSION RELATIONSHIP AND ASSOCIATED STATISTICS FOR EACH VI AT HARVEST

VI	N	R^2	STD DEV	B-VALUE	STD ERROR	F-VALUE	PROB >F
AVI	218	.43	7.35	-	-	39.62	.0001
VARIABLES							
Intercept	-	-	-	24.24	-	-	-
Wheat	-	-	-	-6.92	1.44	22.99	.0001
SOILMO2	-	-	-	7.13	0.92	60.47	.0001
SM3FO	-	-	-	-0.01	0.003	15.71	.0001
AVIMSM2	-	-	-	-0.21	0.025	70.53	.0001
DVI	218	.43	7.35	-	-	39.78	.0001
VARIABLES							
Intercept	-	-	-	26.86	-	-	-
Wheat	-	-	-	-8.14	1.48	30.32	.0001
SOILMO2	-	-	-	8.50	0.94	81.96	.0001
SM3FO	-	-	-	-0.01	0.003	12.77	.0004
DVIMSM2	-	-	-	-0.18	0.02	71.03	.0001
LAI	218	.42	7.42	-	-	30.64	.0001
VARIABLES							
Intercept	-	-	-	28.94	-	-	-
Wheat	-	-	-	-5.99	1.44	17.23	.0001
SOILMO2	-	-	-	5.11	1.55	10.92	.0011
SM3CU	-	-	-	0.29	0.16	5.32	.0220
SM3FO	-	-	-	-0.05	0.02	7.70	.0060
LAIMSM2	-	-	-	-0.37	0.05	59.43	.0001
KVI	218	.43	7.32	-	-	40.47	.0001
VARIABLES							
Intercept	-	-	-	28.36	-	-	-
Wheat	-	-	-	-8.46	1.48	32.57	.0001
SOILMO2	-	-	-	8.79	0.94	86.81	.0001
SM3FO	-	-	-	-0.10	0.003	9.84	.0020
KVIMSM2	-	-	-	-0.31	0.04	73.12	.0001
TVI6	218	.42	7.36	-	-	39.42	.0001
VARIABLES							
Intercept	-	-	-	-59.04	-	-	-
Wheat	-	-	-	-7.13	1.45	24.15	.0001
SM3FO	-	-	-	-0.10	0.003	8.89	.0032
TVIMSM2	-	-	-	-72.49	8.41	74.27	.0001
TVIASM2	-	-	-	82.14	8.83	86.55	.0001
TVI7	218	.43	7.32	-	-	40.51	.0001
VARIABLES							
Intercept	-	-	-	25.21	-	-	-
Wheat	-	-	-	-6.79	1.43	22.43	.0001
SOILMO2	-	-	-	35.77	3.52	103.49	.0001
SM3FO	-	-	-	-0.01	0.003	14.22	.0002
TVIMSM2	-	-	-	-35.69	4.17	73.25	.0001
PVI6	218	.40	7.52	-	-	35.58	.0001
VARIABLES							
Intercept	-	-	-	30.70	-	-	-
Wheat	-	-	-	-8.86	1.55	32.43	.0001
SOILMO2	-	-	-	8.39	0.96	76.17	.0001
SM3FO	-	-	-	-0.006	0.003	3.76	.0540
PVIMSM3	-	-	-	-0.30	0.04	58.19	.0001
PVI7	218	.44	7.23	-	-	42.76	.0001
VARIABLES							
Intercept	-	-	-	28.32	-	-	-
Wheat	-	-	-	-8.55	1.46	34.16	.0001
SOILMO2	-	-	-	8.48	0.92	84.63	.0001
SM3FO	-	-	-	-0.10	0.003	9.65	.0021
PVIMSM3	-	-	-	-0.52	0.06	80.12	.0001

a low of 7.23 for the PVI7 to a high of 7.52 for the PVI6. Again, the differences between the yield relationship defined for the VI's was small. Little variation in the independent variables entering the regression relationships was found due to the relatively high correlation between the VI's.

The independent variables proving to be the most significant at harvest were the VI multiplied by surface soil moisture and subsurface soil moisture. Other variables proving to be significant at harvest were the code variable differentiating between wheat types and the sum of surface and subsurface soil moisture raised to the fourth power. The sum of surface and subsurface soil moisture variable raised to the third power was found to be significant in the LAI relationship while the VI added to subsurface soil moisture was found to be significant in the TVI6 relationship.

3.3 RELATIONSHIPS TO PLANT DENSITY AND PLANT HEIGHT

3.3.1 Plant Density. The relationship between plant density and the independent variables produced relatively strong relationships at tillering and stem extension. The analysis was limited to these two growth stage intervals, because of the method used to record the plant density data (refer to Section 1.4.2).

The coefficient of determination and standard deviation between the observed and estimated plant density at tillering were .62 and .46, respectively (Table 3-8). Those variables which were significant in explaining the variation in plant density at tillering included the AVI, DVI, PVI7, growth stage, surface and subsurface soil moisture. All of the VI's were included in the list of independent variables. Interactive terms similar o those defined for the yield analysis were not defined for the plant density or plant height analysis.

Growth stage was identified as the most significant variable followed by the AVI and surface soil moisture. The tillering growth stage interval spans growth stages 1-5 during which significant changes in plant density occur. During tillering the plant density is low and the soils greatly affect the reflectance responses recorded by Landsat. The VI's cannot effectively measure the increase in plant density due to the resolution of the Landsat allowing the predominance of soil response over plant response.

At stem extension the coefficient of determination and the standard deviation were .74 and .48, respectively (Table 3-8). The variables which were significant in explaining the variation in plant density included the TVI6, LAI, wheat type and subsurface soil moisture.

TVI6 was identified as being the most significant variable followed by the code variable differentiating between wheat types, the LAI and subsurface soil moisture. The predominance of soils over plant matter was negligible during stem extension. Those VI's computed from band 6 seemed to measure plant density more accurately than those computed from band 7. Both the TVI6 and LAI are based, in part, on band 6.

TABLE 3-8 PLANT DENSITY REGRESSION RELATIONSHIP AND ASSOCIATED STATISTICS AT TILLERING AND STEM EXTENSION

	N	R^2	STD DEV	B-VALUE	STD ERROR	F-VALUE	PROB >F
TILLERING	196	.62	.46	-	-	52.31	.0001
VARIABLES							
Intercept	-	-	-	1.65	-	-	-
AVI	-	-	-	0.14	0.03	5.84	.0001
DVI	-	-	-	-0.19	0.04	3.25	.0001
PVI7	-	-	-	0.20	0.09	1.05	.0278
GROWSTA	-	-	-	0.42	0.03	33.87	.0001
SOILMO1	-	-	-	0.46	0.10	4.60	.0001
SOILMO2	-	-	-	-0.08	0.03	1.53	.0080
STEM EXTENSION	31	.74	.48	-	-	18.96	.0001
VARIABLES							
Intercept	-	-	-	-39.29	-	-	-
TVI6	-	-	-	44.39	12.54	12.53	.0015
LAI	-	-	-	-0.20	0.07	7.18	.0126
Wheat	-	-	-	-0.58	0.22	7.30	.0120
SOILMO2	-	-	-	-0.37	0.14	6.79	.0149

3.3.2 Plant Height. Relatively strong relationships between plant height and the independent variables were defined at tillering and stem extension. The coefficient of determination and the standard deviation between the observed and estimated plant height at tillering were .66 and 1.40, respectively (Table 3-9). Those variables which were significant in explaining the variation in plant height at tillering included the LAI, growth stage, wheat type, and surface soil moisutre. All of the VI's were included in the list of independent variables. Interactive terms were not defined in this analysis.

Growth stage was identified as the most significant variable followed by the LAI, the code variable differentiating between wheat types and surface soil moisture.

At stem extension the importance of the VI's in explaining the variation in plant height grew stronger. The coefficient of determination and standard deviation at stem extension were .91 and 1.93, respectively (Table 3-9). The variables which proved to be significant were the PVI7, TVI6, growth stage and subsurface soil moisture. The PVI7 proved to be the most significant variable followed closely by growth stage.

TABLE 3-9 PLANT HEIGHT REGRESSION RELATIONSHIP AND ASSOCIATED STATISTICS AT TILLERING AND STEM EXTENSION

	N	R^2	STD DEV	B-VALUE	STD ERROR	F-VALUE	PROB >F
TILLERING	196	.66	1.40	-	-	92.88	.0001
VARIABLES							
Intercept	-	-	-	-1.60	-	-	-
LAI	-	-	-	0.09	0.02	25.74	.0001
GROWSTA	-	-	-	1.25	0.11	130.54	.0001
Wheat	-	-	-	1.41	0.28	23.66	.0001
SOILMO1	-	-	-	0.66	0.31	4.38	.0377
STEM EXTENSION	31	.91	1.93	-	-	51.40	.0001
VARIABLES							
Intercept	-	-	-	131.55	-	-	-
PVI7	-	-	-	2.23	0.33	44.67	.0001
TVI6	-	-	-	-152.53	32.41	22.14	.0001
GROWSTA	-	-	-	2.14	0.34	38.69	.0001
SOILMO2	-	-	-	2.43	0.55	19.61	.0001

REFERENCES

A. Hass, R.H., Deering, D.W., Rouse, Jr., J.W., and Schell, J.H., "Monitoring Vegetation from Landsat for use in Range Management" NASA Earth Resources Survey Symposium, June 1975, Vol. I-A, NASA TMX-58168

B. Colwell, Robert N., "Erts -1 Imagery and High Flight Photographs as Aids to Fire Hazard Appraisal at the NASA San Pablo Reservoir Test Resources Technology Satellite - 1, March 5-19, 1973, Section A, NASA SP-327.

C. Aaronson, A.C., Buchman, P.E., Wescott, T., and Fires, R.E., "A Landsat Agricultural Monitoring Program", Landsat Agricultural Monitoring Program (LAMP '78), General Electric Comapny, Space Division, Beltsville, Md., (Proposal No. U 77650AR, June 20, 1977).

D. Heilman, J.L., Kanemasu, E.T., Bagley, J.O., Rasmussen, V.P., "Evaluating Soil Moisture and Yield of Winter Wheat in the Great Plains Using Landsat Data", Remote Sensing of Environment, June 1977.

E. Thompson, D.R., "Monitoring Drought by Landsat", Thirth-Second Annual Meeting Soil Conservation Socieity of America, Richmond, Virginia, August 7-10, 1977, JSC-12983.

F. Aaronson, A.C., Davis, L.L., and May, G.A., "Results of the Vegetative Index Correlation Study", Crop Condition Assessment Division, Foreign Agricultural Service (6-TM, February 9, 1979).

SEP 18 1979

VEGETATIVE INDEX TRANSFORMATIONS

$$AVI = 2CH^*4 - CH2$$

$$DVI = 2.4CH4 - CH2$$

$$GVI = -.283CH1 - .660CH2 + .577CH3 + .388CH4$$

$$LAI = \frac{41.325CH1}{CH2} - \frac{42.45CH1}{CH3}$$

$$KVI = GVI - \text{SOIL LINE}^{**}$$

$$PVI6 = (-.498-.457CH2+.498CH3)^2+(2.734+.498CH2-.543CH3)^2$$

$$PVI7 = (.355CH4-.149CH2)^2+(.355CH2-.852CH4)^2$$

$$TVI6 = \frac{CH3-CH2}{CH3+CH2} +1.0$$

$$TVI7 = \frac{CH4-CH2}{CH4+CH2} +1.0$$

* CHANNEL 1 = CH1 = BAND 4
CHANNEL 2 = CH2 = BAND 5
CHANNEL 3 = CH3 = BAND 6
CHANNEL 4 = CH4 = BAND 7

** The value computed by the soil line equation is equal to a constant of "-7" after the Landsat data have been sun angle and haze corrected. The value computed by the soil line does vary without sun angle and/or haze corrections.

SEP 18 1979

APPENDIX B

CORRELATIONS BETWEEN VARIABLES

BY WHEAT TYPE (SPRING AND WINTER)

CORRELATIONS AND SIGNIFICANCE LEVELS AT HEADING AND FLOWERING FOR SPRING WHEAT FIELDS

HEADING

	AVI	PVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	GROW	YLD	SM1	SM2
GROW	.01	.01	.02	-.03	-.03	-.002	.03	-.06	.01	1.00			
	.9463	.9585	.8922	.8554	.8554	.9891	.8617	.7318	.9589				
YIELD	.55	.53	.63	.57	.57	.60	.59	.56	.53	-.14	1.00		
	.0007	.0010	.0001	.0003	.0003	.0002	.0002	.0004	.0010	.4287			
SM1	.33	.32	.30	.34	.34	.30	.30	.33	.32	.12	.14	1.00	
	.0554	.0560	.0746	.0473	.0473	.0797	.0779	.0509	.0561	.50	.4143		
SM2	.40	.41	.38	.43	.43	.37	.36	.46	.41	-.36	.65	.10	1.00
	.0174	.0144	.0252	.0103	.0103	.0271	.0307	.0058	.0144	.0320	.0001	.5556	

FLOWERING

	AVI	PVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	GROW	YLD	SM1	SM2
GROW	-.01	.002	-.12	.00	.00	-.07	-.07	.01	.00	1.00			
	.9381	.9820	.2614	1.0000	1.0000	.5242	.5188	.9002	.9833				
YIELD	.13	.10	.34	.15	.15	.32	.27	.12	.10	.24	1.00		
	.2213	.3571	.0008	.1359	.1359	.0020	.0079	.2614	.3564	.0213			
SM1	.28	.29	.18	.24	.24	.20	.23	.23	.29	-.40	-.26	1.00	
	.0055	.0048	.0829	.0183	.0183	.0577	.0244	.0272	.0047	.0001	.0128		
SM2	.22	.20	.32	.22	.22	.32	.31	.18	.20	-.01	.50	.12	1.00
	.0311	.0524	.0015	.0345	.0345	.0015	.0023	.0888	.0524	.8969	.0001	.2465	

SEP 18 1979

CORRELATIONS AND SIGNIFICANCE LEVELS AT STEM EXTENSION
AND HEADING FOR WINTER WHEAT FIELDS

STEM EXTENSION

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	PLTH	PLTD	GROW	YLD	SM1	SM2
PLTH	.84	.85	.78	.82	.82	.76	.79	.83	.85	1.00					
	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001						
PLTD	.78	.78	.80	.80	.80	.83	.80	.80	.78	.54	1.00				
	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0080					
GROW	.75	.74	.76	.77	.77	.79	.76	.76	.74	.69	.73	1.00			
	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0002	.0001				
YIELD	.51	.50	.51	.47	.47	.46	.52	.42	.50	.45	.32	.19	1.00		
	.0125	.0139	.0126	.0246	.0246	.0274	.0103	.0444	.0140	.0306	.1389	.3847			
SM1	-.41	-.42	-.34	-.42	-.42	-.34	-.35	-.46	-.42	-.67	-.24	-.43	.02	1.00	
	.0536	.0431	.1088	.0462	.0462	.1143	.1025	.0270	.0428	.0005	.2692	.0380	.9149		
SM2	-.002	-.005	-.04	-.08	-.08	-.09	-.01	-.13	-.01	.23	-.38	-.24	.33	-.02	1.00
	.9893	.9788	.8505	.7006	.7006	.6840	.9624	.5513	.9714	.2907	.0751	.2620	.1248	.9409	
								HEADING							
GROW	-.19	-.22	-.21	-.24	-.24	-.22	-.18	-.31	-.22	—	—	1.00			
	.4083	.3494	.3666	.3048	.3048	.3526	.4525	.1763	.3498	—	—				
YIELD	.60	.61	.64	.61	.61	.62	.60	.63	.61	—	—	-.35	1.00		
	.0054	.0045	.0025	.0040	.0040	.0033	.0051	.0027	.0045	—	—	.1346			
SM1	.53	.56	.50	.60	.60	.53	.49	.69	.56	—	—	-.59	.56	1.00	
	.0164	.0097	.0246	.0047	.0047	.0150	.0283	.0007	.0097	—	—	.0063	.0108		
SM2	-.42	-.45	-.38	-.49	-.49	-.42	-.39	-.56	-.45	—	—	.41	-.42	-.91	1.00
	.0638	.0453	.0936	.0282	.0282	.0670	.0908	.0102	.0454	—	—	.0704	.0643	.0001	

APPENDIX C

CORRELATIONS BETWEEN VARIABLES
BY FIELD SIZE

CORRELATIONS AND SIGNIFICANCE LEVELS AT STEM EXTENSION, HEADING AND FLOWERING
FOR FIELDS GREATER THAN OR EQUAL TO 30 PIXELS

STEM EXTENSION

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	PLTH	PLTD	GROW	YLD	SM1	SM2
PLTH	.84	.85	.77	.83	.83	.76	.79	.84	.85	1.00					
	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001						
PLTD	.73	.71	.76	.73	.73	.79	.75	.71	.71	.46	1.00				
	.0002	.0003	.0001	.0002	.0002	.0001	.0001	.0003	.0003	.0340					
GROW	.68	.66	.72	.69	.69	.74	.72	.67	.66	.63	.69	1.00			
	.0007	.0010	.0002	.0005	.0005	.0001	.0002	.0009	.0010	.0019	.0005				
YIELD	.55	.55	.55	.52	.52	.50	.56	.48	.55	.50	.37	.25	1.00		
	.0094	.0103	.0099	.0162	.0162	.0193	.0081	.0282	.0103	.0218	.0998	.2771			
SM1	-.01	-.04	-.08	-.03	-.03	.07	.08	-.09	-.03	-.26	.13	.10	.29	1.00	
	.9634	.8751	.7345	.9044	.9044	.7494	.7357	.7098	.8783	.2486	.5677	.6743	.2065		
SM2	-.14	-.11	-.21	-.17	-.17	-.24	-.19	-.16	-.11	.12	-.55	-.51	.13	-.32	1.00
	.5475	.6187	.3484	.4489	.4489	.2864	.41	.4976	.6170	.6145	.0101	.0179	.5743	.1546	

HEADING

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	PLTH	PLTD	GROW	YLD	SM1	SM2
GROW	-.31	-.31	-.30	-.36	-.36	-.32	-.30	-.39	-.31	–	–	1.00			
	.0967	.0918	.1107	.0505	.0505	.0796	.1121	.0326	.0918	–	–				
YIELD	.70	.70	.74	.74	.74	.75	.73	.74	.70	–	–	-.47	1.00		
	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	–	–	.0088			
SM1	.60	.60	.56	.68	.68	.63	.59	.70	.60	–	–	-.47	.69	1.00	
	.0005	.0004	.0013	.0001	.0001	.0002	.0006	.0001	.0004	–	–	.0052	.0001		
SM2	.26	.25	.27	.31	.31	.28	.25	.33	.25	–	–	-.43	.56	.32	1.00
	.1692	.1735	.1523	.0944	.0944	.1333	.1766	.0736	.1733	–	–	.0173	.0013	.0849	

CORRELATIONS AND SIGNIFICANCE LEVELS AT STEM EXTENSION, HEADING AND FLOWERING
FOR FIELDS GREATER THAN OR EQUAL TO 30 PIXELS (Continued)

FLOWERING

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	PLTH	PLTD	GROW	YLD	SM1	SM2
GROW	-.17	-.17	-.21	-.15	-.15	-.15	-.17	-.16	-.17	—	—	1.00			
	.2366	.2279	.1400	.2782	.2782	.2714	.2309	.2611	.2278	—	—				
YIELD	.16	.12	.35	.18	.18	.34	.31	.13	.12	—	—	-.30	1.00		
	.2691	.3939	.0115	.2105	.2105	.0123	.0272	.3501	.3931	—	—	.0327			
SM1	.32	.34	.18	.30	.30	.23	.24	.30	.34	—	—	-.36	-.26	1.00	
	.0187	.0142	.1925	.0306	.0306	.1066	.0858	.0310	.0142	—	—	.0076	.0571		
SM2	.21	.19	.30	.22	.22	.31	.29	.19	.19	—	—	.05	.46	.06	1.00
	.1265	.1654	.0294	.1238	.1238	.0263	.0360	.1861	.1654	—	—	.6960	.0005	.6675	

SEP 18 1979

CORRELATIONS AND SIGNIFICANCE LEVELS AT STEM EXTENSION, HEADING AND FLOWERING FOR FIELDS GREATER THAN OR EQUAL TO 40 PIXELS

STEM EXTENSION

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	PLTH	PLTD	GROW	YLD	SM1	SM2
PLTH	.74 .0004	.75 .0003	.69 .0015	.73 .0006	.73 .0006	.68 .0020	.70 .0011	.75 .0003	.75 .0003	1.00					
PLTD	.79 .0001	.78 .0001	.80 .0001	.79 .0001	.79 .0001	.82 .0001	.80 .0001	.76 .0003	.78 .0001	.49 .0366	1.00				
GROW	.80 .0001	.78 .0001	.85 .0001	.78 .0001	.78 .0001	.84 .0001	.85 .0001	.73 .0006	.78 .0001	.69 .0015	.78 .0001	1.00			
YIELD	.23 .3477	.22 .3882	.28 .2576	.22 .3743	.22 .3743	.25 .3181	.28 .2586	.18 .4830	.22 .3872	.20 .4176	.31 .2017	.42 .0856	1.00		
SM1	-.22 .3749	-.26 .2958	-.10 .6836	-.25 .3219	-.25 .3219	-.11 .0677	-.12 .6348	-.33 .1838	-.26 .2976	-.60 .0082	.08 .7494	.02 .9451	.26 .2885	1.00	
SM2	-.47 .0480	-.45 .0625	-.51 .0286	-.47 .0459	-.47 .0459	-.51 .0284	-.50 .0358	-.43 .0736	-.45 .0621	-.08 .75	-.71 .0010	-.55 .0158	-.27 .28	-.38 .1209	1.00

HEADING

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	PLTH	PLTD	GROW	YLD	SM1	SM2
GROW	-.30 .1329	-.30 .1315	-.31 .1172	-.35 .0808	-.35 .0808	-.33 .1030	-.30 .1372	-.37 .0584	-.30 .1314	— —	— —	1.00			
YIELD	.70 .0001	.69 .0001	.75 .0001	.74 .0001	.74 .0001	.75 .0001	.72 .0001	.75 .0001	.69 .0001	— —	— —	-.48 .0121	1.00		
SM1	.63 .0005	.63 .0006	.67 .0002	.71 .0001	.71 .0001	.70 .0001	.66 .0002	.72 .0001	.63 .0006	— —	— —	-.48 .0134	.75 .0001	1.00	
SM2	.27 .1866	.26 .1899	.28 .1575	.32 .1143	.32 .1143	.28 .1583	.27 .1811	.34 .0918	.26 .1900	— —	— —	.45 .0214	.61 .0009	.32 .1110	1.00

CORRELATIONS AND SIGNIFICANCE LEVELS AT STEM EXTENSION, HEADING AND FLOWERING FOR FIELDS GREATER THAN OR EQUAL TO 40 PIXELS (Continued)

FLOWERING

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	PLTH	PLTD	GROW	YLD	SM1	SM2
GROW	-.17	-.17	-.25	-.16	-.16	-.20	-.19	-.16	-.17	—	—	1.00			
	.3830	.3875	.1862	.4033	.4033	.3073	.3214	.3936	.3871	—	—				
YIELD	.37	.35	.45	.39	.39	.45	.44	.36	.35	—	—	.21	1.00		
	.0507	.0639	.0137	.0381	.0381	.0131	.0161	.0561	.0037	—	—	.2825			
SM1	.35	.37	.18	.34	.34	.25	.25	.35	.37	—	—	-.47	-.08	1.00	
	.0606	.0469	.3354	.0709	.0709	.1957	.1931	.0627	.0469	—	—	.0092	.6927		
SM2	.36	.35	.38	.37	.37	.38	.38	.35	.36	—	—	.03	.45	.12	1.00
	.0552	.0571	.0441	.0507	.0507	.0407	.0401	.0589	.0571	—	—	.8671	.0144	.5483	

CORRELATIONS AND SIGNIFICANCE LEVELS AT STEM EXTENSION, HEADING AND FLOWERING FOR FIELDS GREATER THAN OR EQUAL TO 50 PIXELS

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	PLTH	PLTD	GROW	YLD	SM1	SM2
STEM EXTENSION															
PLTH	.72	.73	.68	.70	.70	.66	.69	.71	.68	1.00					
	.0038	.0030	.0079	.0051	.0051	.0104	.0059	.0043	.0079						
PLTD	.86	.84	.89	.86	.86	.90	.89	.82	.89	.54	1.00				
	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0004	.0001	.0471					
GROW	.77	.75	.83	.75	.75	.82	.83	.68	.83	.68	.81	1.00			
	.0012	.0022	.0002	.0020	.0020	.0003	.0002	.0067	.0002	.0079	.0004				
YIELD	.14	.12	.19	.12	.12	.15	.19	.07	.19	.22	.30	.29	1.00		
	.6273	.6787	.5123	.6745	.6745	.6067	.5069	.8034	.5069	.4440	.3008	.1630			
SM1	-.09	-.14	.05	-.12	-.12	.03	.02	-.22	-.14	-.48	.17	.18	.27	1.00	
	.7643	.6393	.8758	.6848	.6848	.9154	.9413	.4525	.6424	.0837	.5524	.5464	.3425		
SM2	-.54	-.51	-.62	-.55	-.54	-.60	-.60	-.48	-.51	-.06	-.71	-.62	-.26	-.50	1.00
	.0436	.0636	.0188	.0434	.0434	.0229	.0240	.0846	.0632	.8485	.0038	.0187	.3721	.0660	
HEADING															
GROW	-.35	-.36	-.34	-.39	-.39	-.38	-.35	-.41	-.36	–	–	1.00			
	.1883	.1856	.2082	.1514	.1514	.1655	.1970	.1298	.1852	–	–				
YIELD	.63	.63	.68	.67	.67	.67	.64	.68	.63	–	–	-.47	1.00		
	.0110	.0121	.0052	.0062	.0062	.0058	.0096	.0052	.0121	–	–	.0768			
SM1	.70	.69	.72	.77	.77	.76	.72	.78	.69	–	–	-.43	.66	1.00	
	.0038	.0041	.0026	.0008	.0008	.0011	.0026	.0011	.0041	–	–	.1101	.0072		
SM2	.44	.45	.40	.48	.48	.41	.40	.41	.45	–	–	-.41	.67	.37	1.00
	.1016	.0951	.1336	.0728	.0728	.1277	.1359	.1277	.0951	–	–	.1294	.0059	.1741	

CORRELATIONS AND SIGNIFICANCE LEVELS AT STEM EXTENSION, HEADING AND FLOWERING
FOR FIELDS GREATER THAN OR EQUAL TO 50 PIXELS (Continued)

FLOWERING

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	PLTH	PLTD	GROW	YLD	SM1	SM2
GROW	-.17	-.18	-.15	-.17	-.17	-.14	-.11	-.20	-.18	—	—	1.00			
	.4358	.4005	.4819	.4308	.4308	.5146	.6105	.3539	.4002	—	—				
YIELD	.31	.29	.38	.33	.33	.39	.38	.30	.29	—	—	.32	1.00		
	.1504	.1767	.0707	.1258	.1258	.0664	.0706	.1692	.1763	—	—	.1397			
SM1	.39	.40	.23	.37	.37	.29	.29	.38	.41	—	—	-.70	-.08	1.00	
	.0664	.0546	.2812	.0779	.0779	.1763	.1715	.0730	.0545	—	—	.0002	.7050		
SM2	.39	.38	.41	.38	.38	.41	.42	.36	.38	—	—	-.03	.29	.12	1.00
	.0675	.0728	.0523	.0715	.0715	.0538	.0454	.0902	.0728	—	—	.8819	.1757	.5779	

SEP 18 1979

APPENDIX D

CORRELATIONS BETWEEN VARIABLES
BY APU

CORRELATIONS AND SIGNIFICANCE LEVELS AT FLOWERING FOR FIELDS IN APU 19

FLOWERING

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	GROW	YLD	SM1	SM2
GROW	.03	.05	-.19	.02	.02	-.14	-.10	.04	.05	1.00			
	.8682	.7979	.3293	.9079	.9079	.4715	.6202	.8345	.7996				
YIELD	.51	.51	.34	.46	.46	.38	.45	.43	.51	.41	1.00		
	.0060	.0055	.0793	.0142	.0142	.0439	.0173	.0208	.0055	.0277			
SM1	.11	.09	.34	.07	.07	.24	.26	.01	.09	-.59	-.05	1.00	
	.5645	.6451	.0791	.7311	.7311	.2114	.1841	.9389	.6435	.0010	.8117		
SM2	.35	.33	.36	.28	.28	.34	.40	.22	.33	-.42	.19	.77	1.00
	.0712	.0819	.0592	.1542	.1542	.0726	.0336	.2593	.0818	.0266	.3301	.0001	

SEP 18 1979

CORRELATIONS AND SIGNIFICANCE LEVELS AT FLOWERING FOR FIELDS IN APU 20

FLOWERING

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	GROW	YLD	SM1	SM2
GROW	.05	.06	-.12	.08	.08	.00	-.05	.10	.06	1.00			
	.7374	.6773	.4193	.5786	.5786	1.00	.7304	.4795	.6776				
YIELD	.14	.14	.06	.15	.15	.13	.12	.15	.14	.33	1.00		
	.3428	.3318	.6741	.2995	.2995	.3751	.4209	.2979	.3317	.0232			
SM1	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	1.00	
	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		
SM2	.06	.08	-.13	.05	.05	-.03	-.02	.06	.08	.25	-.02	.00	1.00
	.6570	.5995	.3876	.7310	.7310	.8187	.8821	.6986	.6004	.0862	.9006	1.00	

SEP 18 1979

CORRELATIONS AND SIGNIFICANCE LEVLES AT HEADING AND FLOWERING FOR FIELDS IN APU 21

HEADING

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	GROW	YLD	SM1	SM2
GROW	-.41 .1128	-.43 .0917	-.39 .1299	-.51 .0434	-.51 .0434	-.35 .1762	-.31 .2334	-.60 .0145	-.43 .0918	1.00			
YIELD	.44 .0846	.47 .0668	.40 .1265	.49 .0511	.49 .0511	.35 .1858	.38 .1487	.56 .0242	.47 .0670	-.65 .0060	1.00		
SM1	.00 1.00	.00 1.00	.00 1.00	.00 1.00	.00 1.00	.00 1.00	.00 1.00	.00 1.00	.00 1.00	.00 1.00	.00 1.00	1.00	
SM2	.15 .5787	.19 .4839	.07 .7959	.23 .3875	.23 .3875	.05 .8649	.03 .9133	.33 .2094	.19 .4844	-.78 .0003	.77 .0005	.00 1.00	1.00

FLOWERING

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	GROW	YLD	SM1	SM2
GROW	-.20 .5306	-.21 .5022	-.17 .5881	-.18 .5688	-.18 .5688	-.15 .6305	-.15 .6308	-.18 .5746	-.21 .5030	1.00			
YIELD	-.19 .5513	-.17 .5989	-.18 .5751	-.15 .6425	-.15 .6475	-.17 .5931	-.23 .4154	-.10 .7600	-.17 .5984	-.15 .6412	1.00		
SM1	.59 .0410	.61 .0350	.58 .0475	.60 .0382	.60 .0382	.58 .0463	.55 .0625	.61 .0334	.61 .0351	.66 .0189	.29 .3583	1.00	
SM2	-.21 .5073	-.19 .5582	-.22 .4921	-.19 .5575	-.19 .5575	-.22 .4891	-.26 .4066	-.15 .6341	-.19 .5575	-.60 .0375	.77 .0037	.56 .0559	1.00

CORRELATIONS AND SIGNIFICANCE LEVELS AT STEM EXTENSION AND HEADING FOR FIELDS IN APU 22

STEM EXTENSION

	AVI	DVI	LAI	GVI	KVI	TVI6	TVI7	PVI6	PVI7	PLTH	PLTD	GROW	YLD	SM1	SM2
PLTH	.86	.87	.80	.85	.85	.81	.82	.86	.87	1.00					
	.0004	.0002	.0017	.0004	.0004	.0015	.0011	.0003	.0002						
PLTD	.76	.76	.76	.76	.76	.79	.76	.76	.76	.69	1.00				
	.0041	.0041	.0040	.0042	.0042	.0023	.0038	.0042	.0042	.0135					
GROW	.60	.62	.55	.60	.60	.58	.58	.62	.62	.84	.70	1.00			
	.0372	.0325	.0611	.0389	.0389	.0455	.0480	.0313	.0389	.0006	.0116				
YIELD	.69	.69	.70	.66	.66	.64	.70	.63	.69	.57	.50	.23	1.00		
	.0126	.0136	.0118	.0188	.0188	.0237	.0110	.0283	.0136	.0533	.0936	.4604			
SM1	.07	.07	.06	.04	.04	.02	.08	.02	.07	.29	-.03	.16	.44	1.00	
	.8243	.8156	.8430	.9080	.9080	.9531	.7935	.9365	.8150	.3540	.9338	.6095	.1556		
SM2	-.05	-.07	-.03	-.06	-.09	-.08	-.03	-.13	-.06	.10	-.14	.04	.19	.60	1.00
	.8616	.8187	.9142	.7709	.7709	.7928	.9142	.6839	.8619	.7516	.6677	.8963	.5460	.0399	
	HEADING														
GROW	-.17	-.16	-.22	-.20	-.20	-.23	-.18	-.20	-.16	—	—	1.00			
	.6140	.6399	.5182	.5440	.5440	.4886	.5901	.5544	.6411	—	—				
YIELD	.50	.49	.61	.49	.49	.58	.61	.44	.49	—	—	.14	1.00		
	.1135	.1289	.0442	.1258	.1258	.0609	.0472	.1750	.1293	—	—	.6748			
SM1	.00	.00	.00	.00	.00	.00	.00	.00	.00	—	—	.00	.00	1.00	
	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	—	—	1.00	1.00		
SM2	-.18	-.23	.19	-.17	-.17	.09	.02	-.23	-.23	—	—	-.58	.09	.00	1.00
	.5962	.4849	.5702	.6233	.6233	.7967	.9572	.4953	.4848	—	—	.0594	.7929	1.00	

SEP 18 1979

LIST OF INDEPENDENT VARIABLES*

A	VI	(VEGETATIVE INDEX)
B	GROWSTA	(GROWTH STAGE)
C	WHEAT	(DUMMY VARIABLE DIFFERENTIATING BETWEEN WHEAT TYPES)
D	SOILMO1	(SURFACE SOIL MOISTURE IN INCHES)
E	SOILMO2	(SUBSURFACE SOIL MOISTURE IN INCHES)
F	SOILMO3	(SUM OF SOILMO1 AND SOILMO2)
G	SM1SQ	(SOILMO1 RAISED TO THE SECOND POWER)
H	SM1CU	(SOILMO1 RAISED TO THE THIRD POWER)
I	SM1FO	(SOILMO1 RAISED TO THE FOURTH POWER)
J	SM2SQ	(SOILMO2 RAISED TO THE SECOND POWER)
K	SM2CU	(SOILMO2 RAISED TO THE THIRD POWER)
L	SM2FO	(SOILMO2 RAISED TO THE FOURTH POWER)
M	SM3SQ	(SOILMO3 RAISED TO THE SECOND POWER)
N	SM3CU	(SOILMO3 RAISED TO THE THIRD POWER)
O	SM3FO	(SOILMO3 RAISED TO THE FOURTH POWER)
P	VIMSM1	(PRODUCT OF VI AND SOILMO1)
Q	VIMSM2	(PRODUCT OF VI AND SOILMO2)
R	VIMSM3	(PRODUCT OF VI AND SOILMO3)
S	VIASM1	(SUM OF VI AND SOILMO1)
T	VIASM2	(SUM OF VI AND SOILMO2)
U	VIASM3	(SUM OF VI AND SOILMO3)
V	VIMGRO	(PRODUCT OF VI AND GROWSTA)

* The independent variables listed were used in the stepwise regression procedure completed for each of the seven growth stage intervals. A single vegetative index and its associated variables were used as inputs to the stepwise procedure. The same associated variables were used in the stepwise procedure completed for each VI.

FIGURE 2-1 LAI VS. GROWTH STAGE

PLOT OF LAI*GROWSTA   LEGEND: A = 1 OBS, B = 2 OBS, ETC.

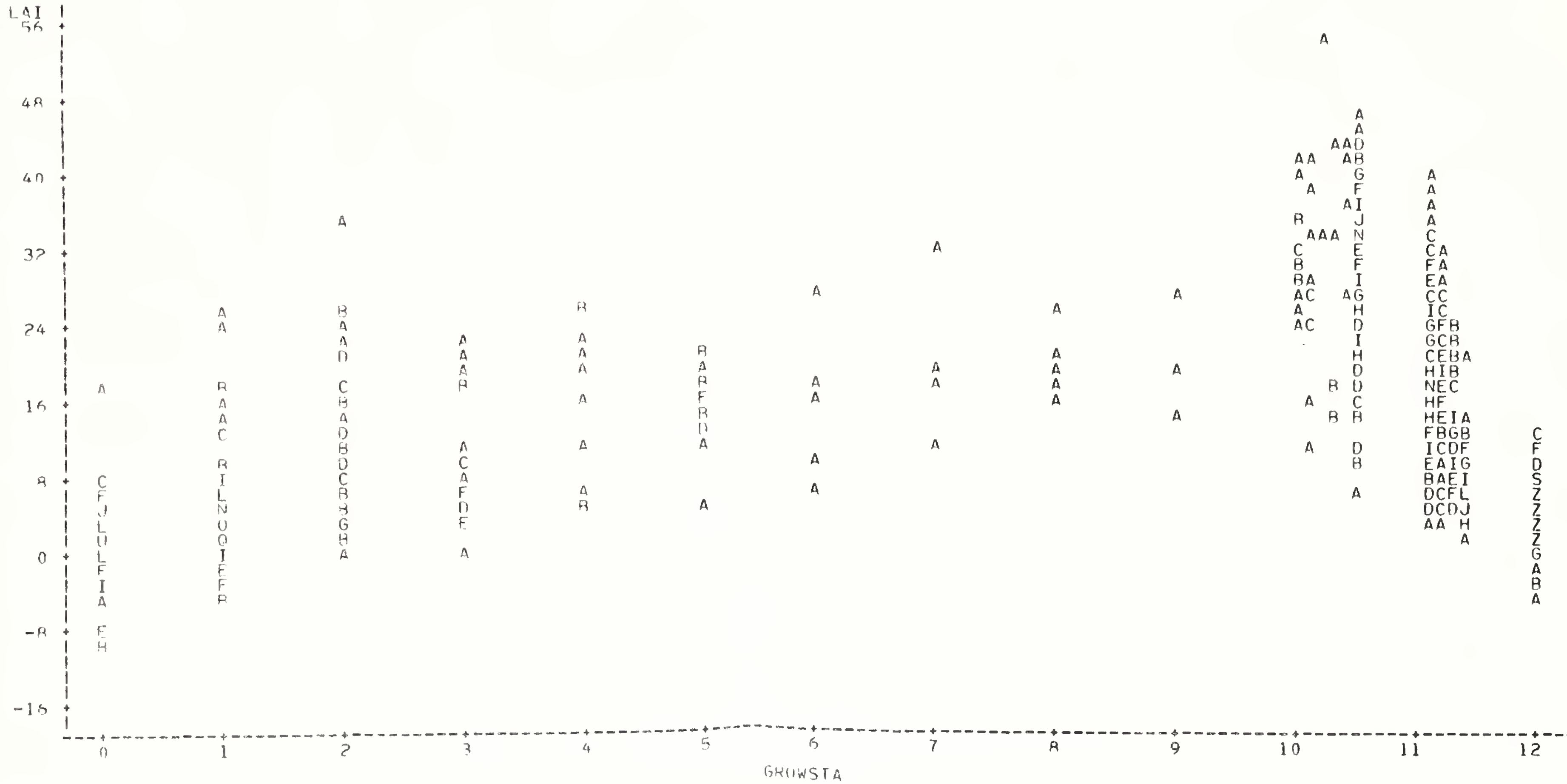


FIGURE 2-2 YIELD VS LAI AT PLANTING

PLOT OF YIELD*LAI LEGEND: A = 1 OBS. B = 2 OBS. ETC.

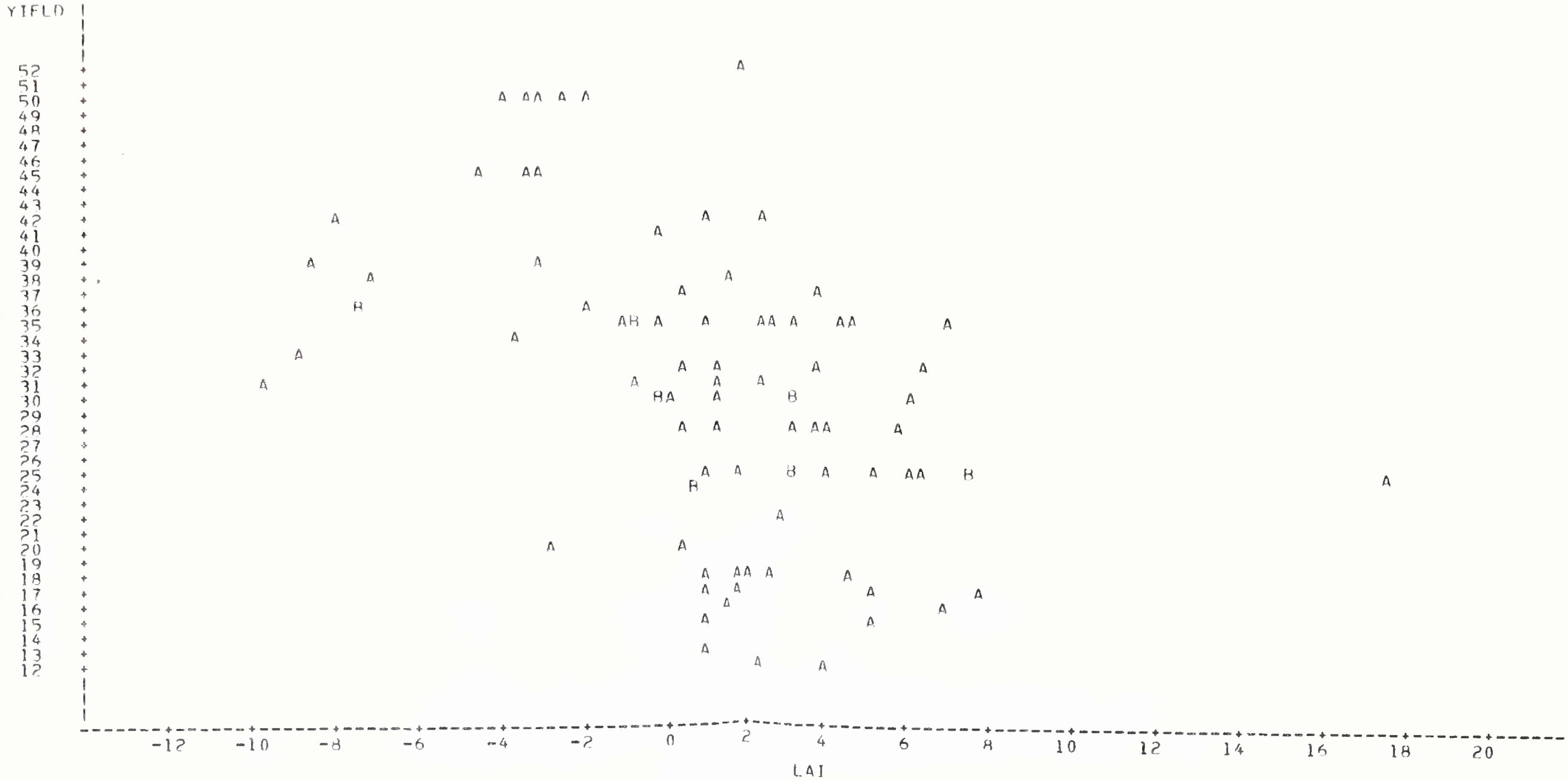


FIGURE 2-3 YIELD VS. LAI AT TILLERING

PLOT OF YIELD*LAI LEGEND: A = 1 OBS, B = 2 OBS, ETC.

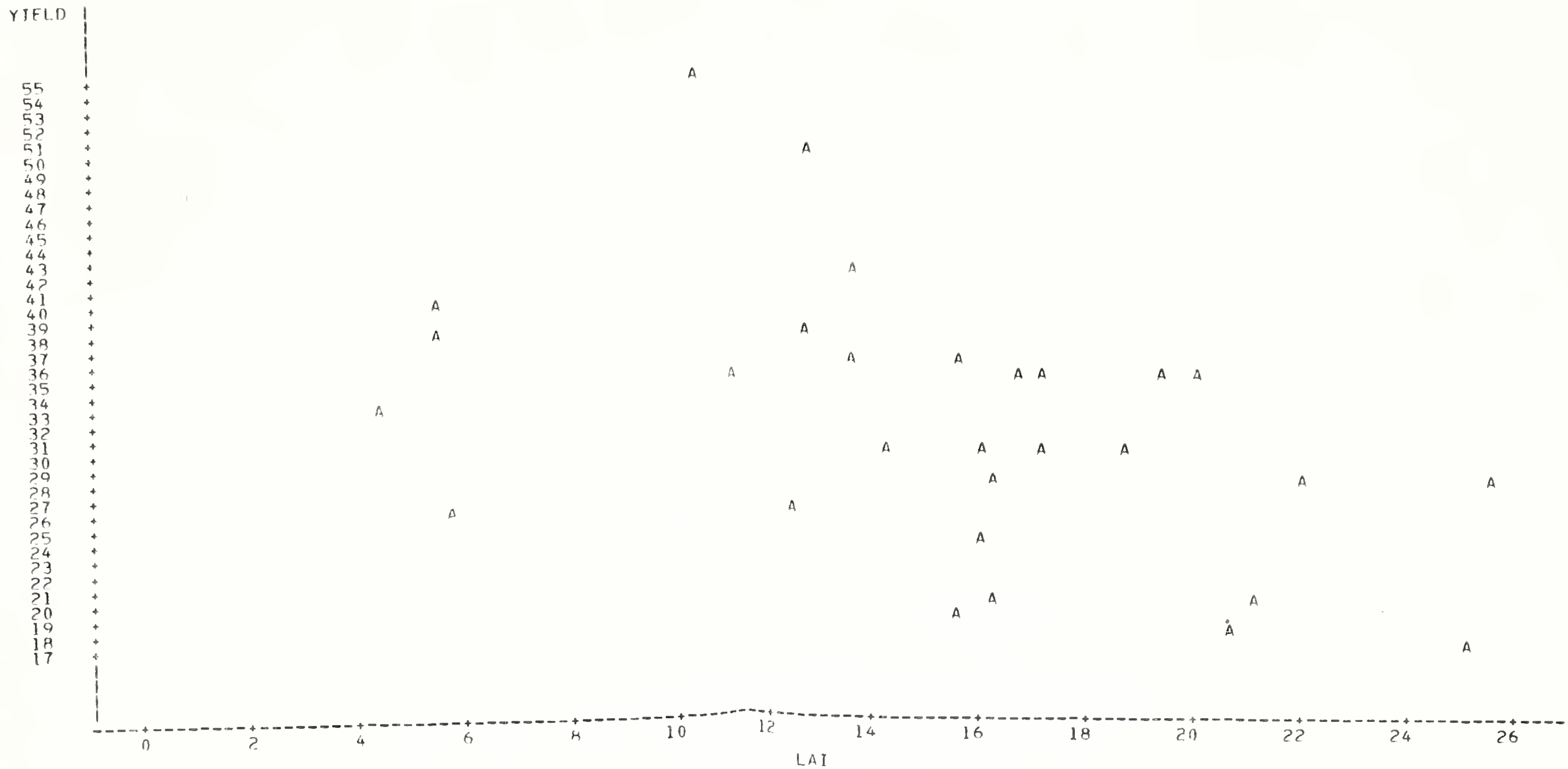


FIGURE 2-4 YIELD VS. LAI AT STEM EXTENSION

PLOT OF YIELD*LAI LEGEND: A = 1 OBS, B = 2 OBS, ETC.

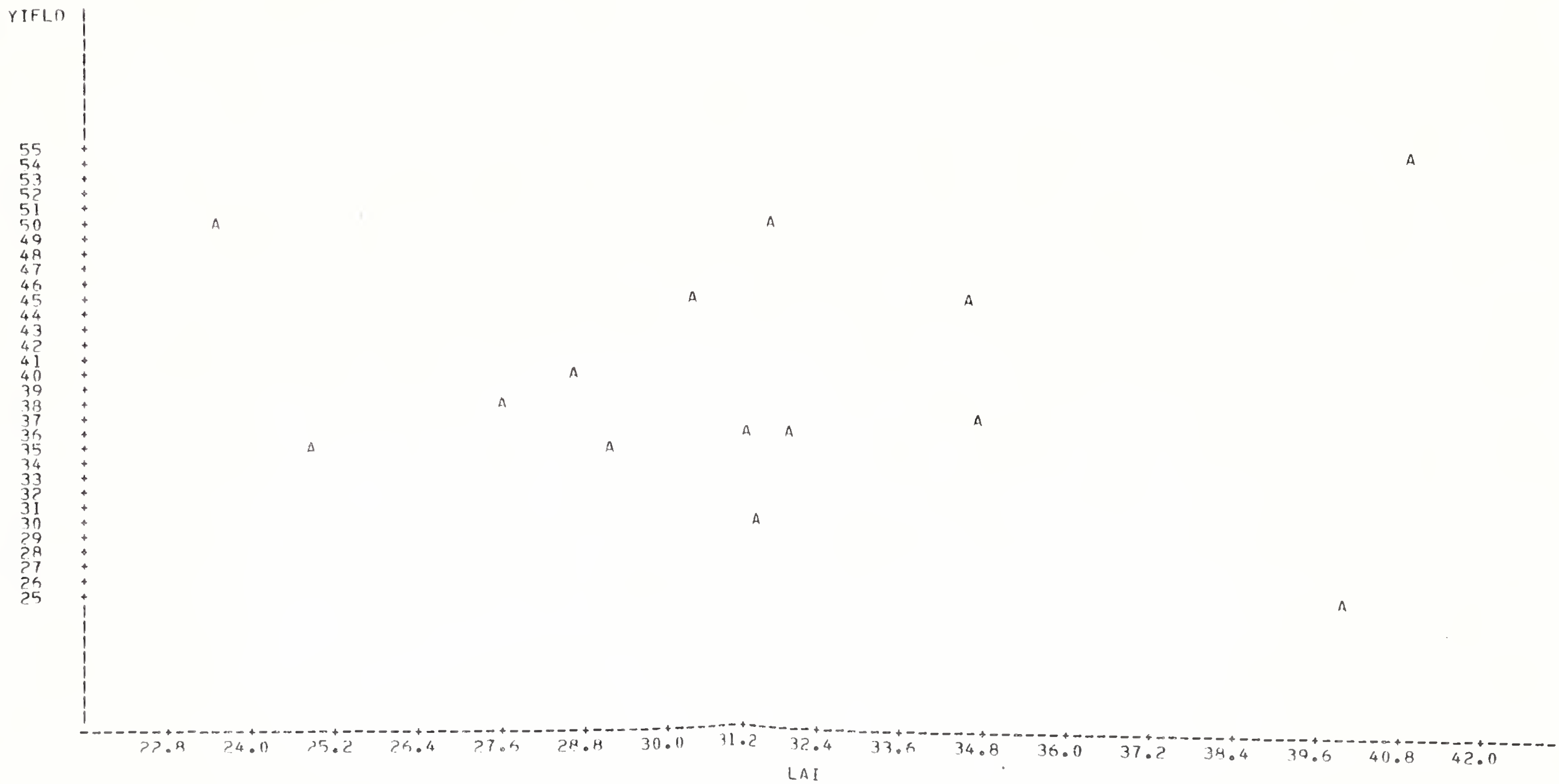


FIGURE 2-5__YIELD VS. LAI AT HEADING

PLOT OF YIELD*LAI   LEGEND: A = 1 OBS, B = 2 OBS, ETC.

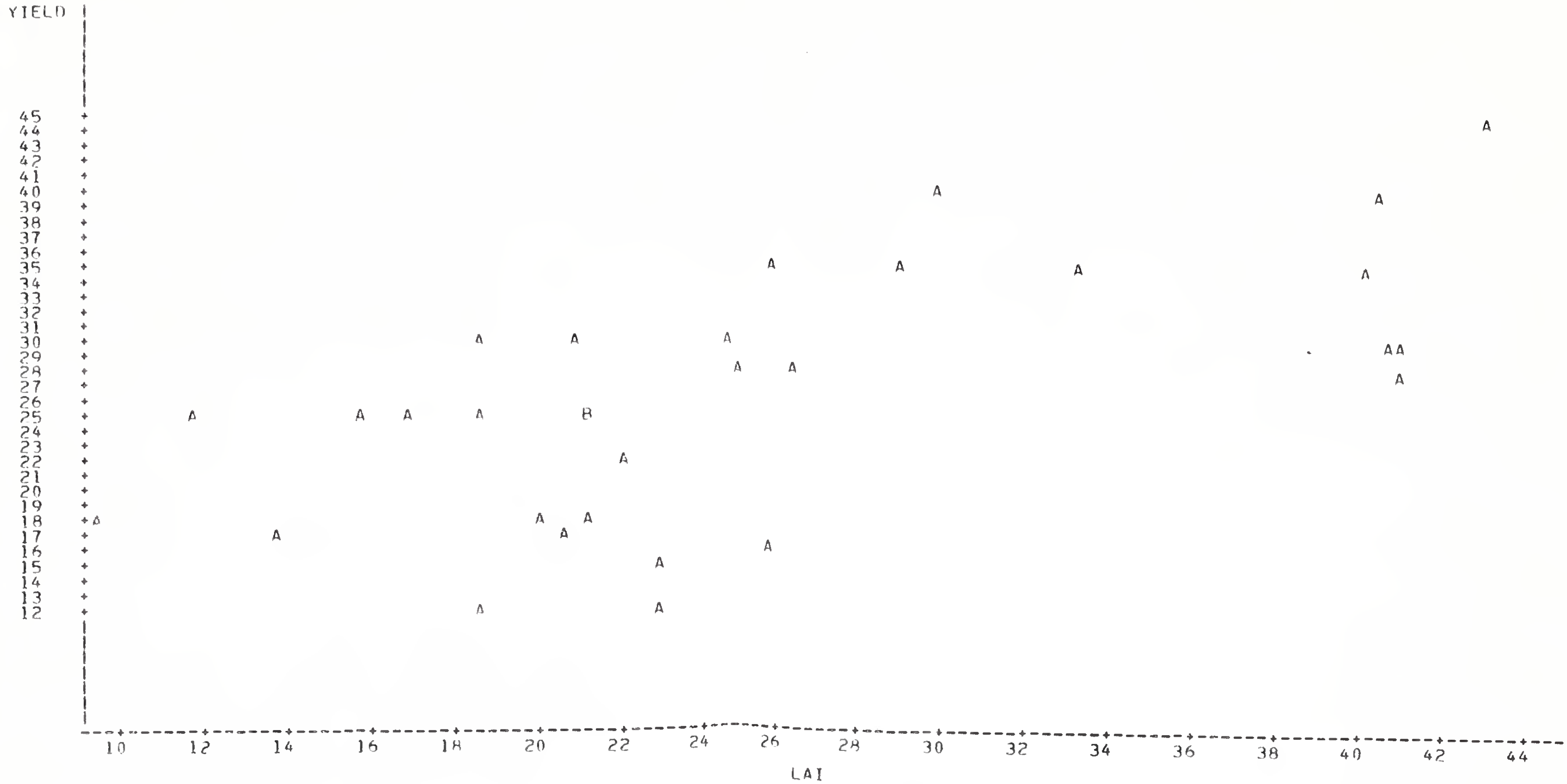


FIGURE 2-6 YIELD VS, LAI AT FLOWERING

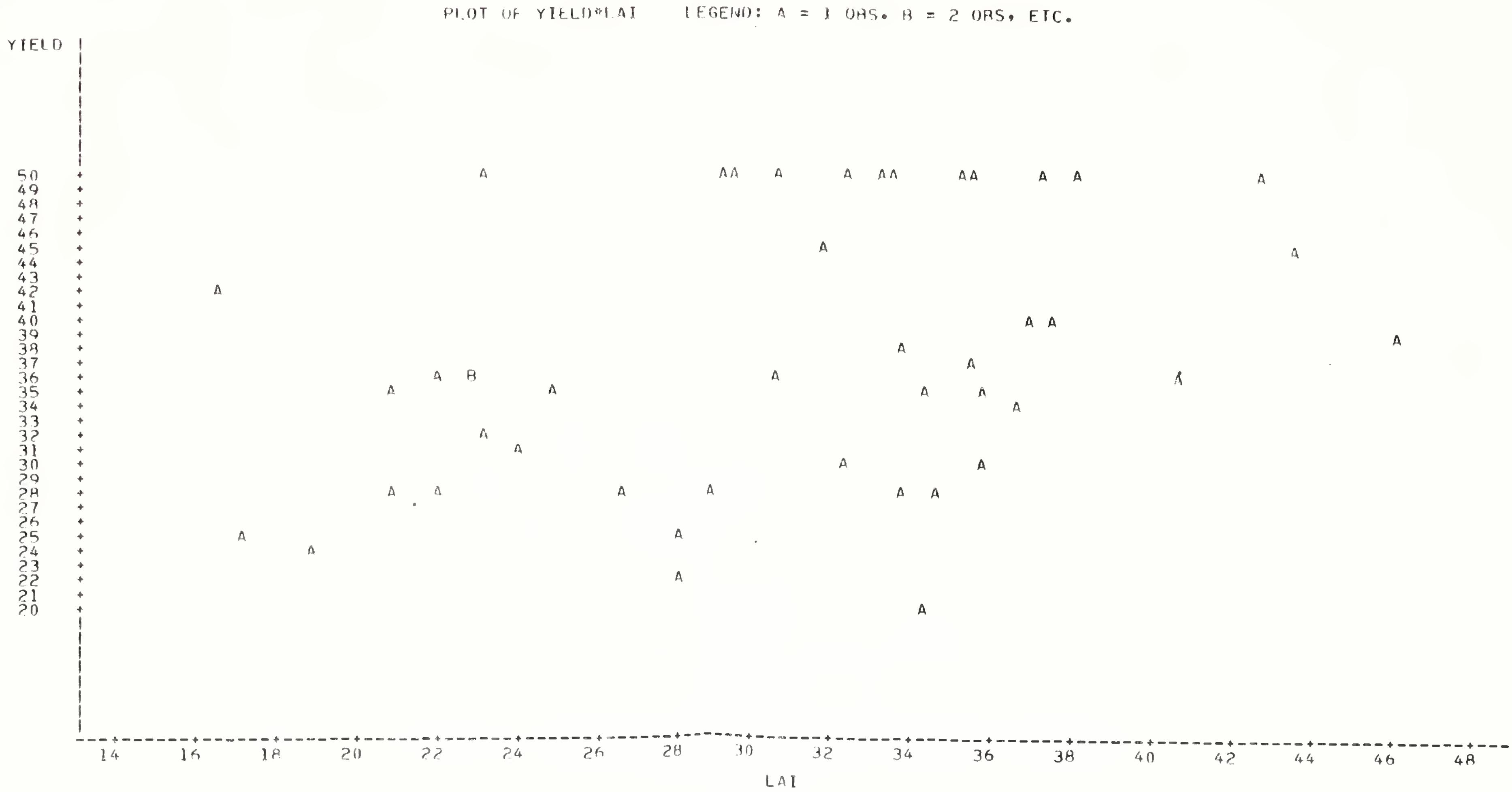


FIGURE 2-7 YIELD VS. LAI AT RIPENING

PLOT OF YIELD*LAI   LEGEND: A = 1 OBS, B = 2 OBS, ETC.

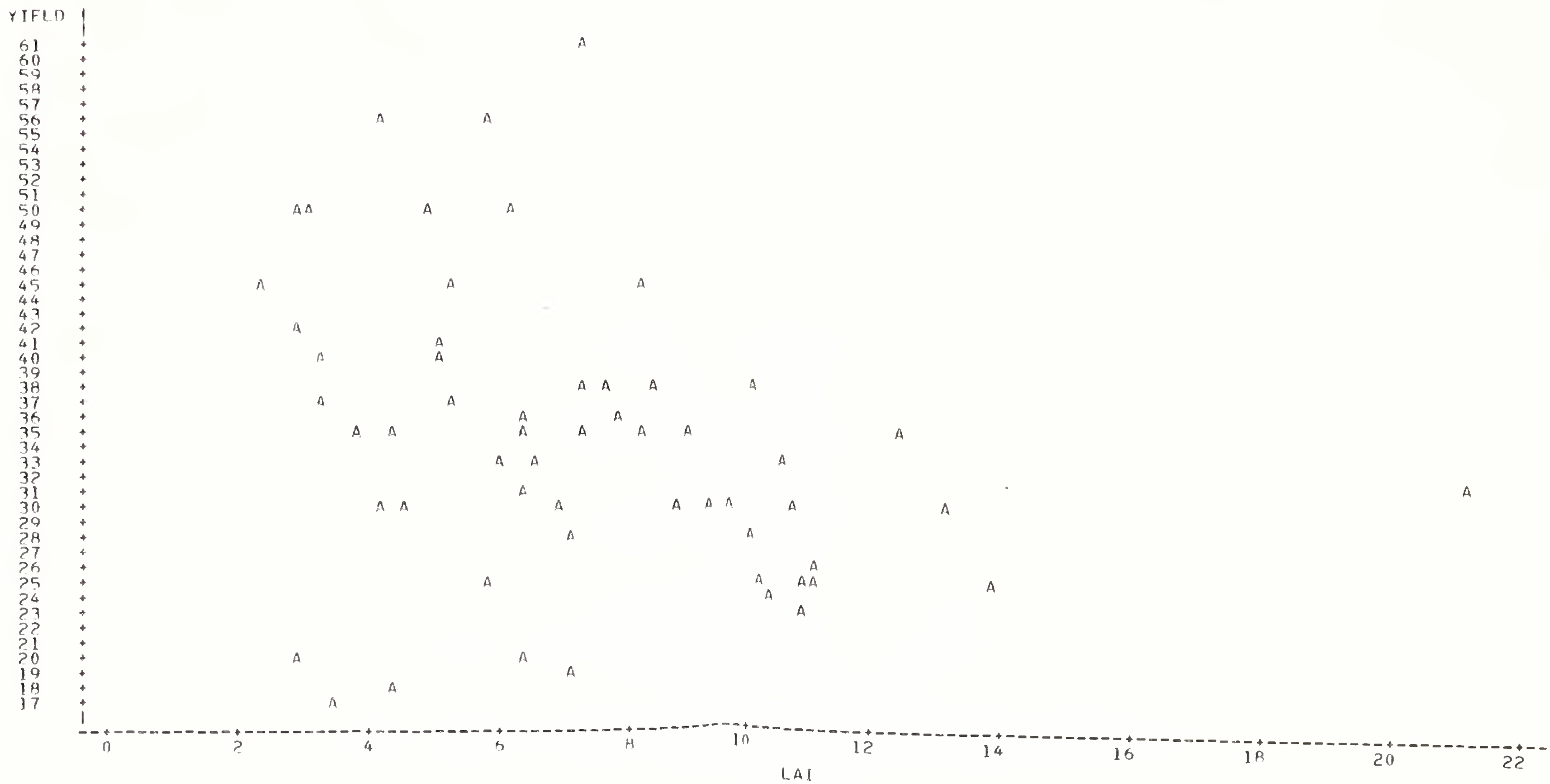


FIGURE 2-8 YIELD VS, LAI AT HARVEST

PLOT OF YIELD*LAI   LEGEND: A = 1 OBS, B = 2 OBS, ETC.

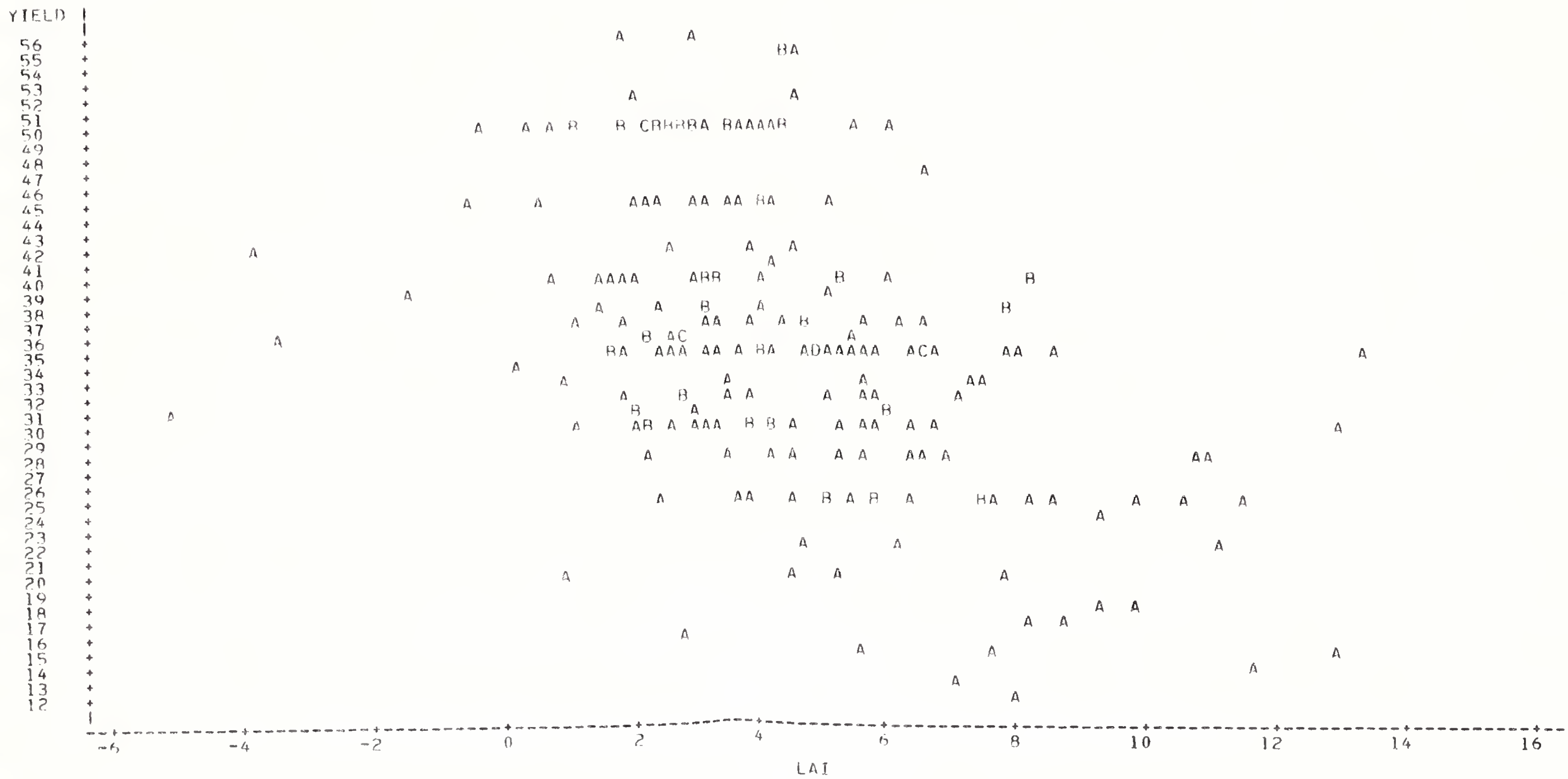


FIGURE 2-9 YIELD VS. SUBSURFACE SOIL MOISTURE AT PLANTING

PLOT OF YIELD*SOILMO2   LEGEND: A = 1 OBS, B = 2 OBS, ETC.

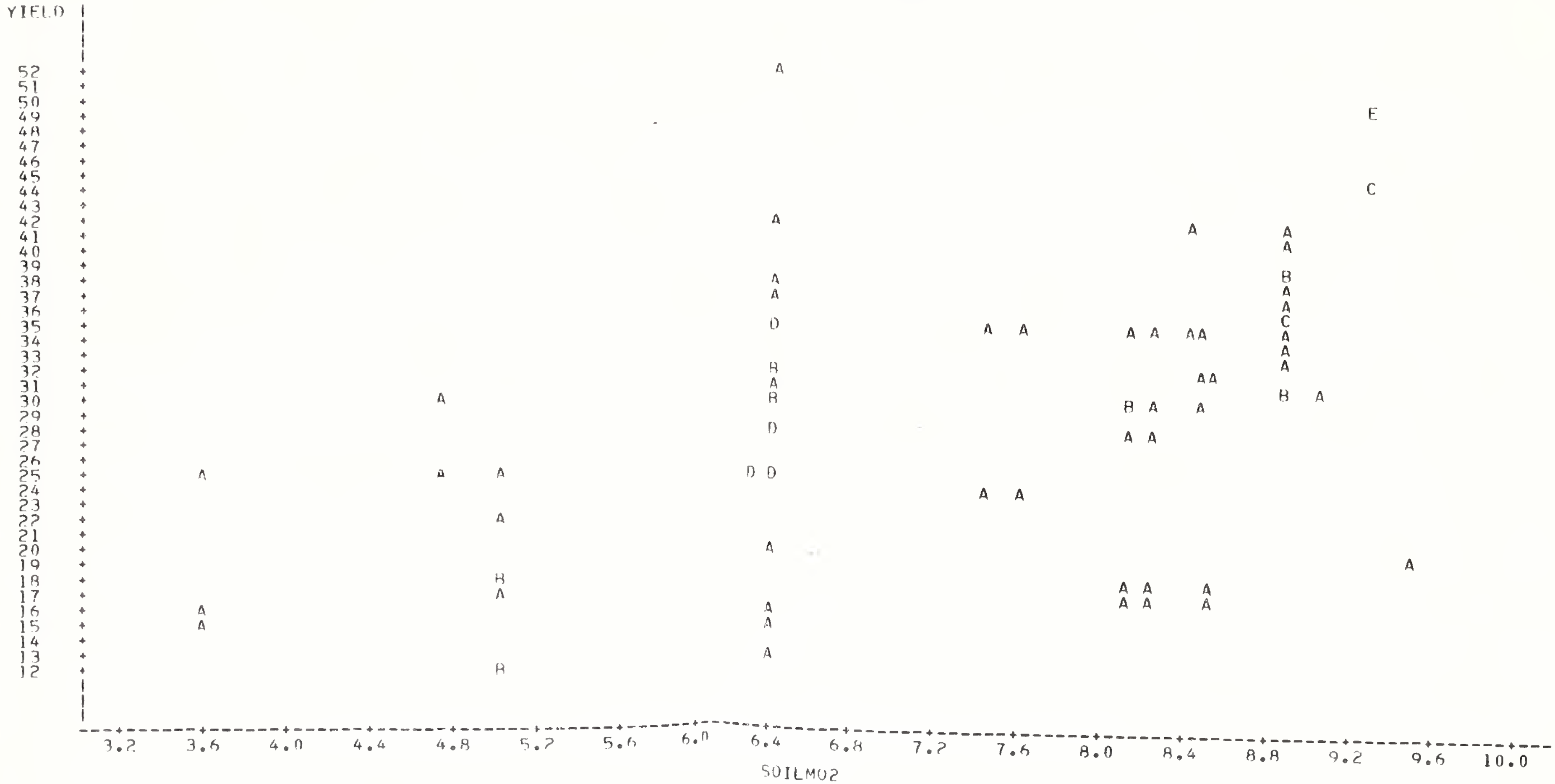


FIGURE 2-10 YIELD VS. SUBSURFACE SOIL MOISTURE AT TILLERING

PLOT OF YIELD*SOILMO2 LEGEND: A = 1 OBS, B = 2 OBS, ETC.

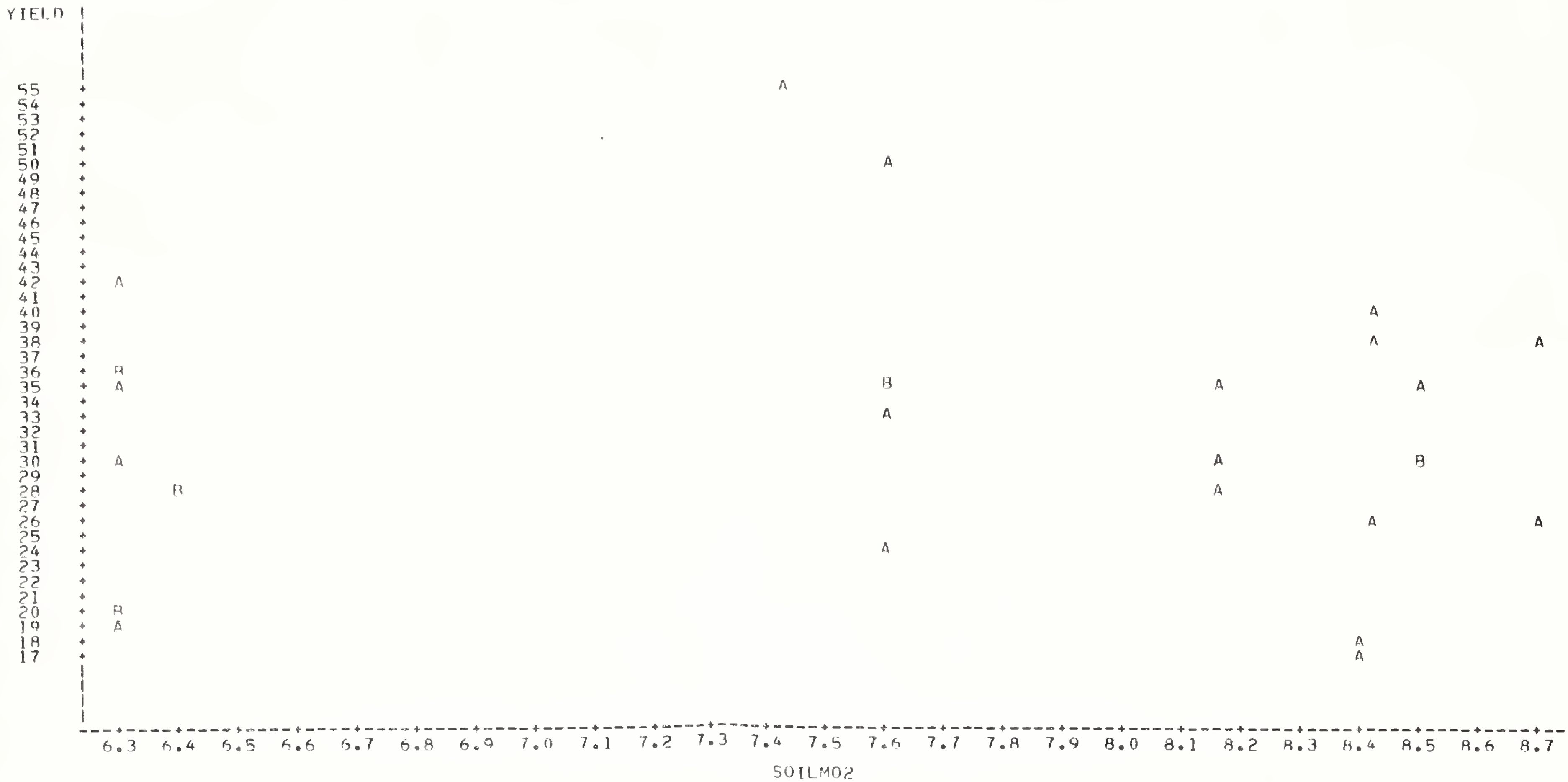


FIGURE 2-11 YIELD VS. SUBSURFACE SOIL MOISTURE AT STEM EXTENSION

PLOT OF YIELD*SOILMO2   LEGEND: A = 1 OBS, B = 2 OBS, ETC.

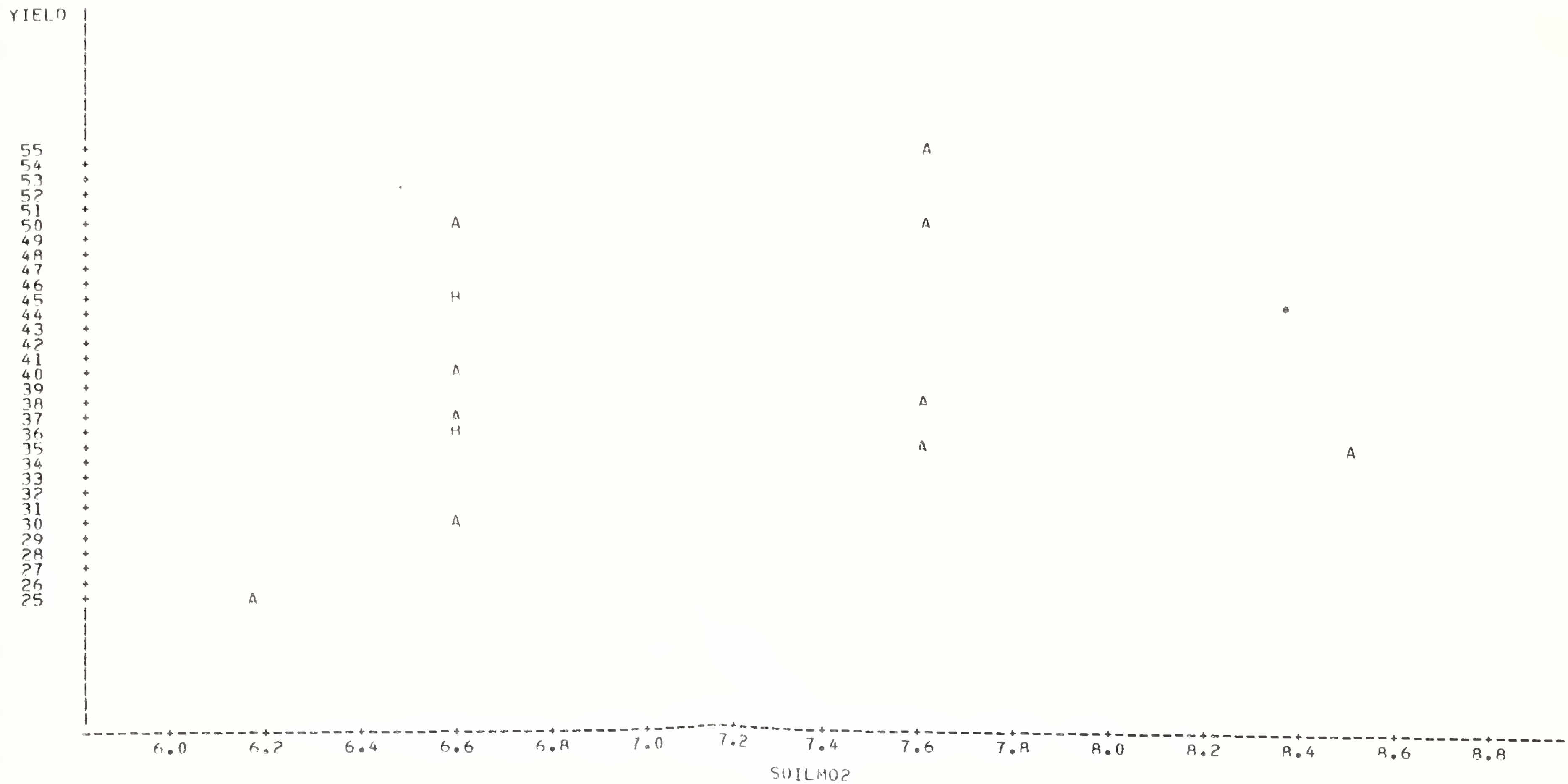


FIGURE 2-12 YIELD VS. SUBSURFACE SOIL MOISTURE AT HEADING

PLOT OF YIELD*SOILMO2   LEGEND: A = 1 OBS, B = 2 OBS, ETC.

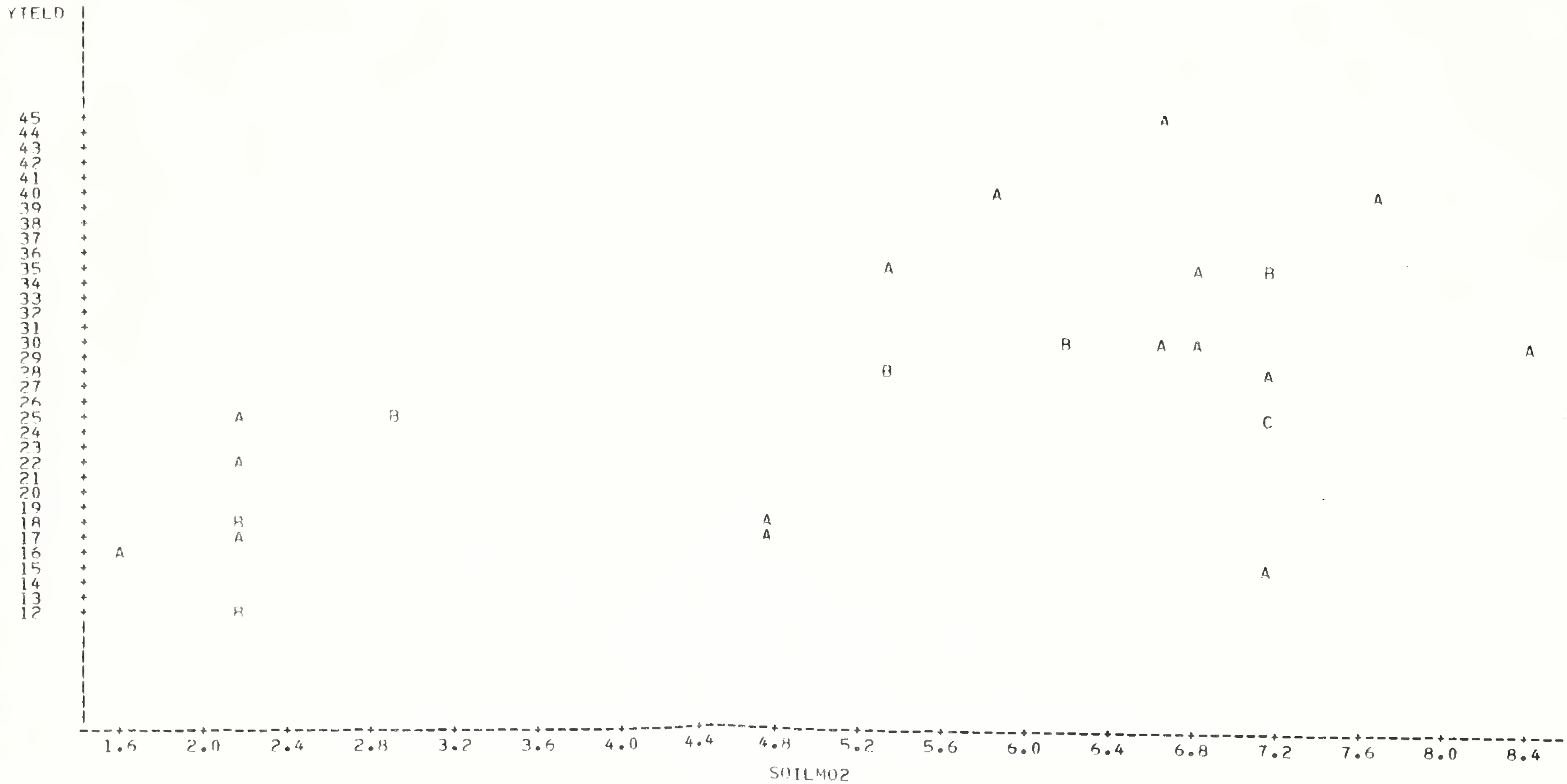


FIGURE 2-13 YIELD VS, SUBSURFACE SOIL MOISTURE AT FLOWERING

PLOT OF YIELD*SOILMO2 LEGEND: A = 1 OBS, B = 2 OBS, ETC.

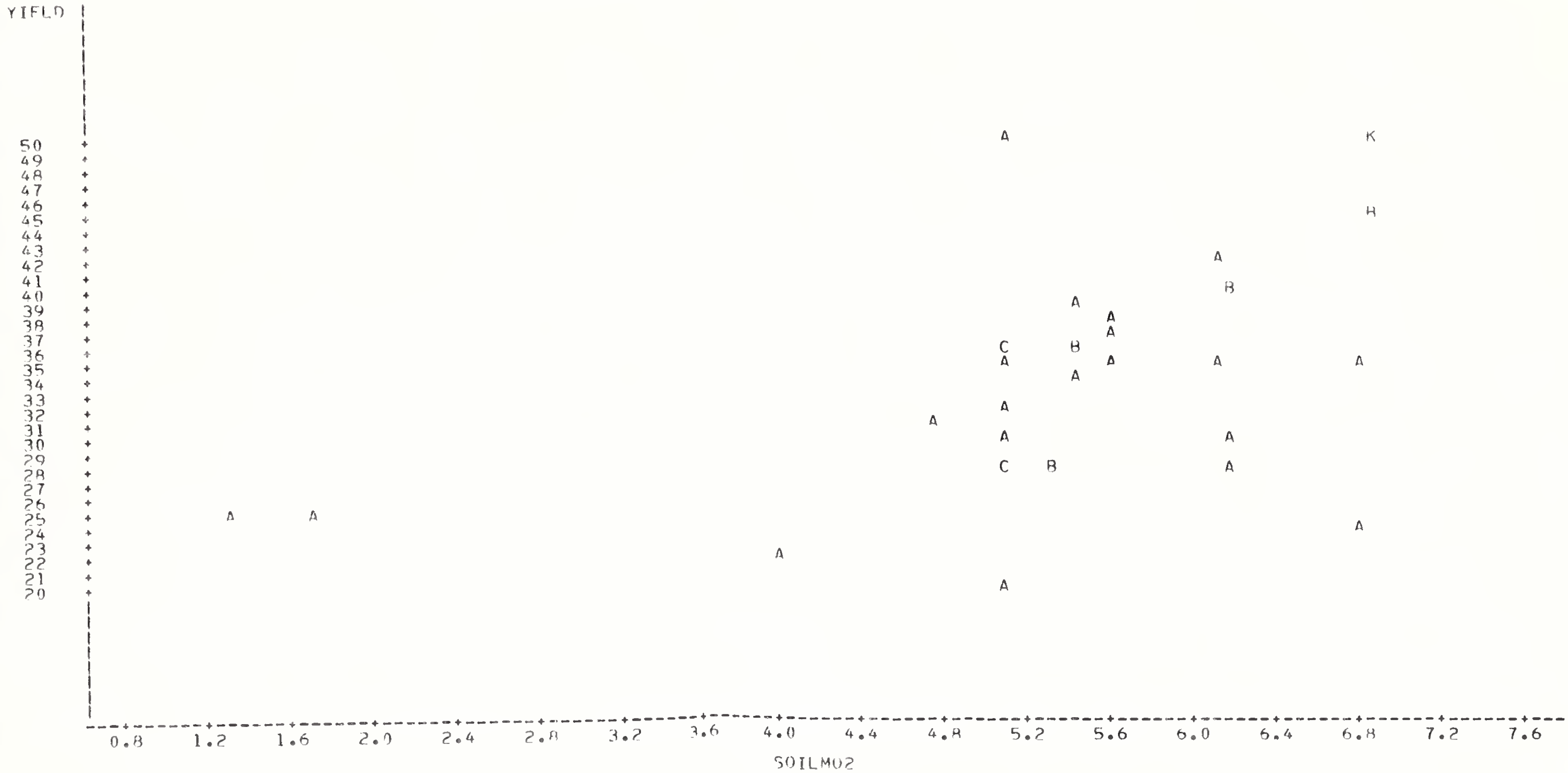


FIGURE 2-14 YIELD VS. SUBSURFACE SOIL MOISTURE AT RIPENING

PLOT OF YIELD*SOILMO2   LEGEND: A = 1 OBS, B = 2 OBS, ETC.

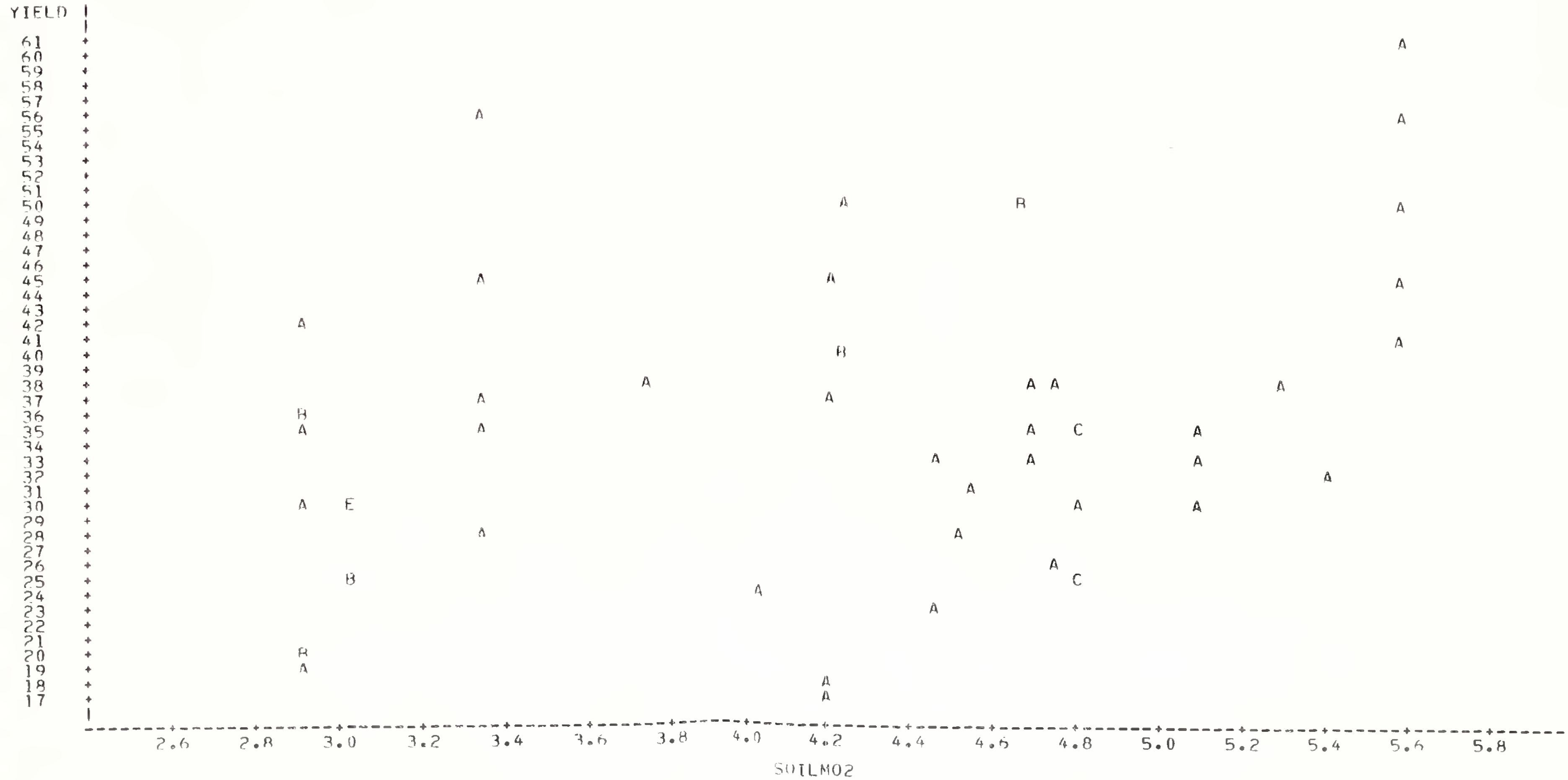


FIGURE 2-15 YIELD VS. SUBSURFACE SOIL MOISTURE AT HARVEST

PLOT OF YIELD*SOILMO2   LEGEND: A = 1 OBS, B = 2 OBS, ETC.

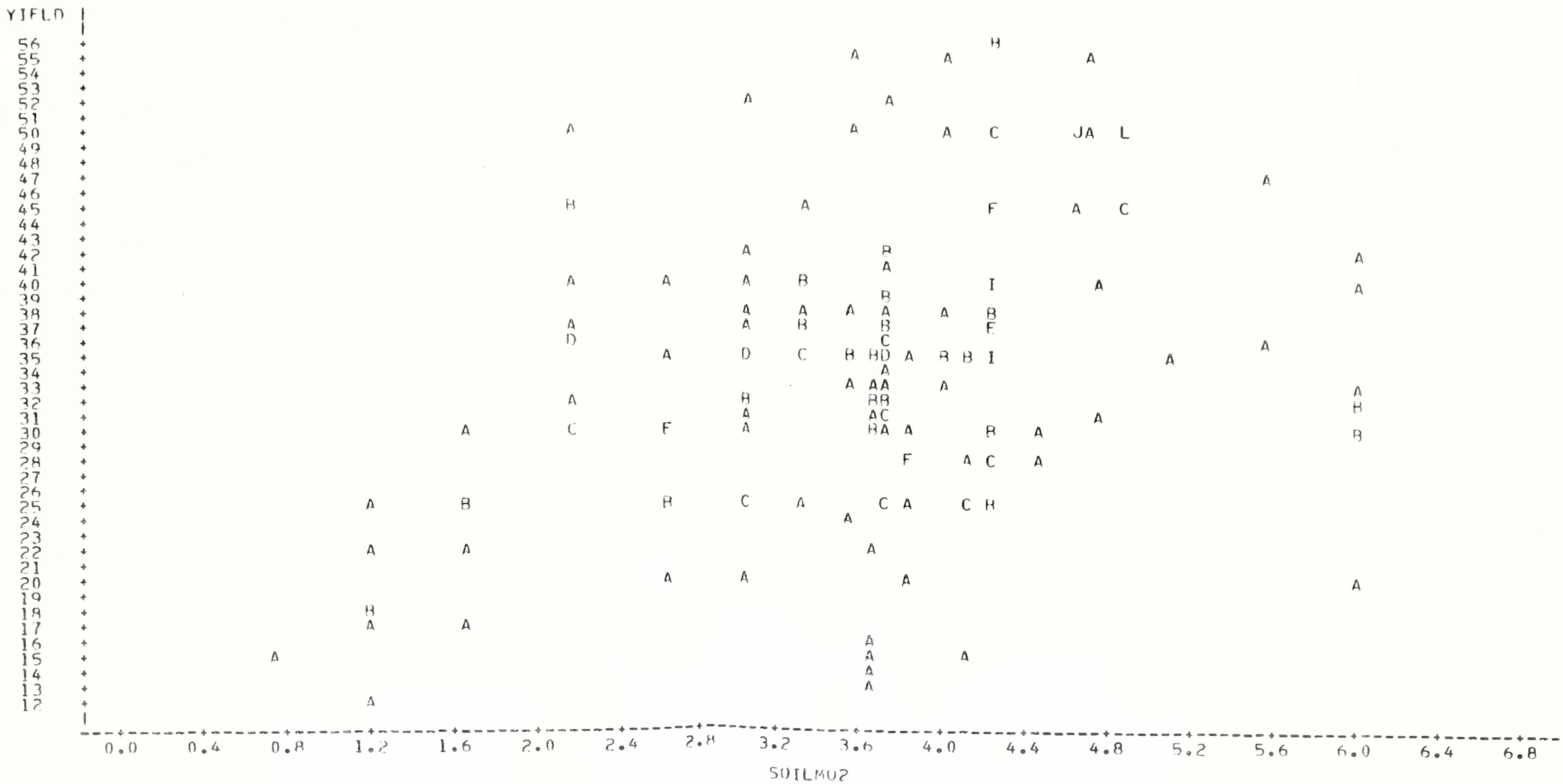
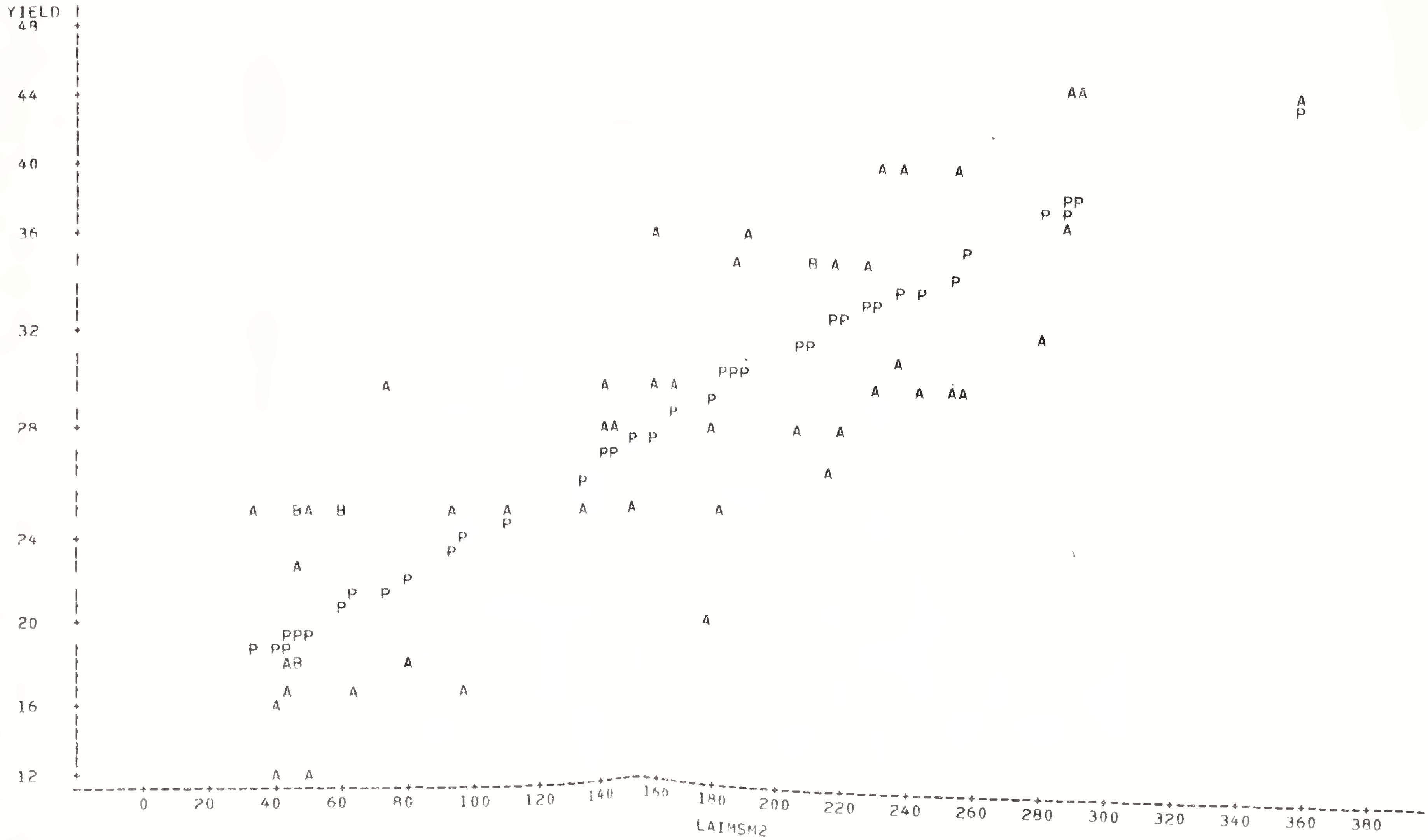


FIGURE 3-1 OBSERVED AND ESTIMATED YIELDS VS. LAIMSM2 AT HEADING

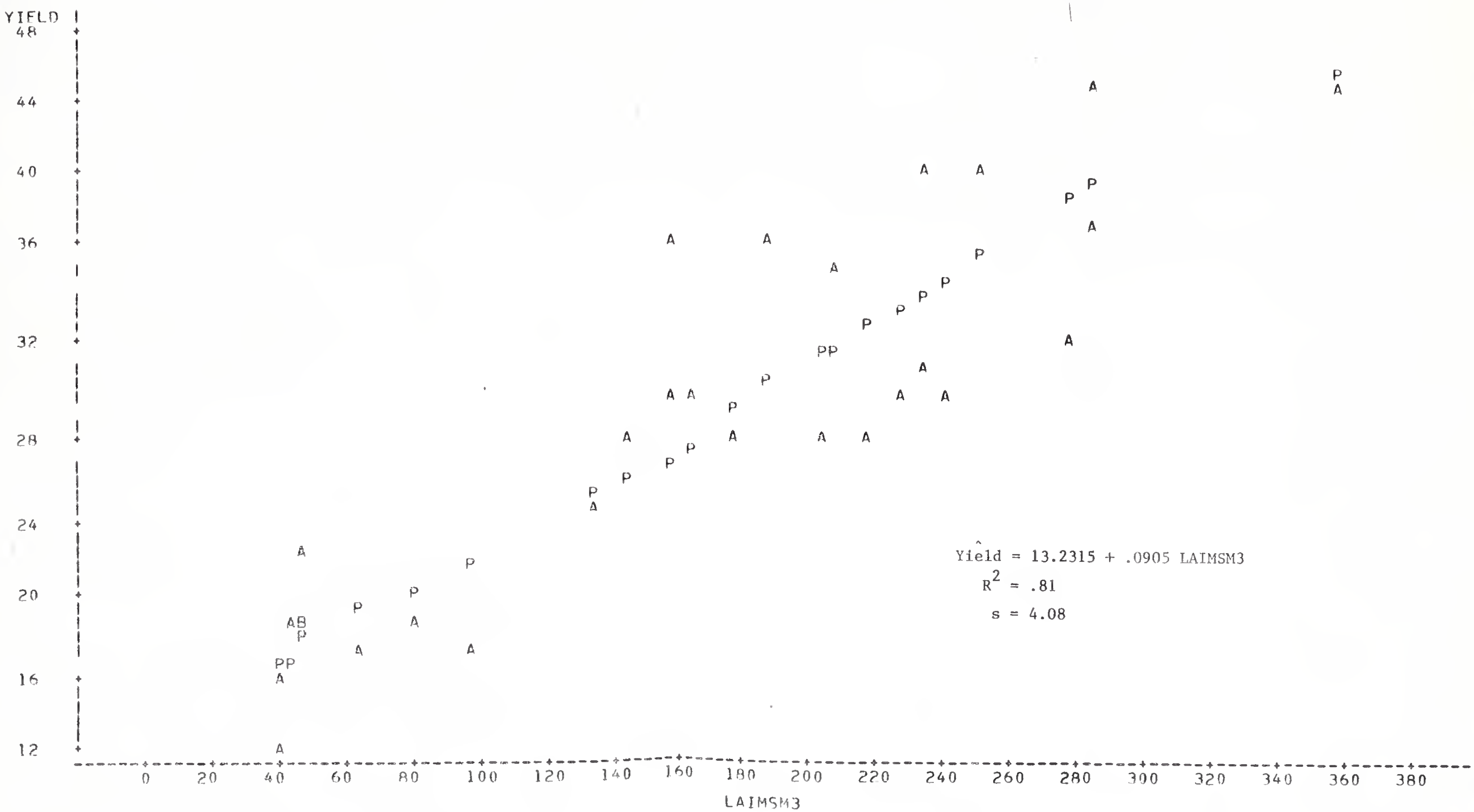
PLOT OF YIELD*LAIMSM2 LEGEND: A = 1 OBS, B = 2 OBS, ETC.
PLOT OF PREDICT*LAIMSM2 SYMBOL USED IS P



NOTE: 15 OBS HIDDEN

FIGURE 3-2 OBSERVED AND ESTIMATED YIELDS
vs. LAIMSM3 AT HEADING, FIELDS GREATER THAN 30 PIXELS

PLOT OF YIELD*LAIMSM3 LEGEND: A = 1 OBS, B = 2 OBS, ETC.
PLOT OF PREDICT*LAIMSM3 SYMBOL USED IS P



NOTE: 6 OBS HIDDEN